ELEMENTS OF RADIO COMMUNICATION

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PREFACE

During the past few years the author has received many suggestions that an introductory volume to his more comprehensive text "Principles of Radio Communication" would fill a real need. It is with the idea of filling such a need that the following simple text in radio has been written. There are thousands of students today, in schools and out, who are sufficiently interested in the subject to desire something more sound and thorough than the many "popular" texts on radio which have appeared, but who have neither the preparation nor time to attempt such a text as the author's "Principles." It is for these students that the "Elements of Radio Communication" has been prepared.

This text is not a collection of excerpts from the larger volume, but has been written entirely anew. The general scheme is the same as that which gave the "Principles" its popularity, namely, a general review of those parts of the alternating current theory which are of fundamental importance in radio, followed by the specific applications of these principles to radio telegraphy and telephony.

Practically no mathematical preparation, more advanced than algebra, is required for complete mastery of this elementary text. It is, nevertheless, sufficiently complete for any radio enthusiast except the engineers specializing in this branch of communication; for these the text forms a reasonable introduction to the subject.

A large proportion of the students of radio are naturally interested in broadcasting, so most of the specific treatment is directed to this field. Reasonable amplifications, power factors, losses, etc., are given for apparatus designed for the broadcasting frequencies. Curves illustrating the performance of radio circuits are in general typical of their action in this band of frequencies.

The last chapter deals with all kinds of receiving sets, from a simple crystal circuit to the most modern a.c. operated receiver. Balanced circuits, push-pull amplifiers, different types of loud speakers, selectivity and fidelity of amplifiers, filters, etc., are all dealt with as thoroughly as space allows.

Accompanying each chapter is a set of problems which should prove of much value to both instructor and student. The problems are for the most part, made up from the circuits of actual radio receivers, so that as the student works them he not only becomes familiar with the principles of radio circuits, but also gains a knowledge of the actual performance of these circuits as they are incorporated in modern radio receivers.

J. H. M.

May 1, 1929.

CONTENTS

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CHAPTER I

SIMPLE LAWS OF ELECTRIC CIRCUITS

1. Applications of the Electric Current.—It is almost impossible today to find any technical development which does not use as an essential feature some action of the electric current. More and more the application of the electric current makes our work easier, or accomplishes a given task more efficiently.

The ordinary doorbell uses the small amount of power delivered from one dry cell; the switch which is closed when the button is pressed permits current from the dry cell to flow through the magnets of the bell and so attract the iron armature to strike the bell. The power and forces involved are small and the distance covered by the electric circuit is measured in feet.

The trolley car draws its power from a generating plant miles away and the amount of power required is measured in hundreds of horsepower, and in the case of heavy subway trains, in thousands of horsepower. The forces involved are produced in just the same way as that of the doorbell, and the laws according to which the power is developed are the same for both.

In the art of refining metals by electrolysis, and in electroplating, the electric current is made to flow through solutions, and instead of developing mechanical forces, as for the doorbell and trolley-car motor, it carries along with it molecules of the metal which is to be refined, or used to coat the article to be plated.

In the ordinary electric light the current is made to flow through a wire and heat it to incandescence. No mechanical forces are utilized and the current does not carry any metal, but in its passage through the wire it agitates the molecules of the

wire to such an extent that they send off electromagnetic waves which we call light. The action of the current in this case is merely to heat the wire; the power used in this lighting service is measured in millions of horsepower.

When one speaks into the mouthpiece of the ordinary telephone set, the sound waves generated in the throat act on the light diaphragm of the microphone and cause the current flowing through the microphone to vary in accordance with the voice waves. These fluctuations in the current may be sent through telephone wires and cables thousands of miles long and at the distant end give off sound waves practically the same as those of the speaker, as suggested in Fig. 1. The amount of power used for this service is very small when compared to that used for light-

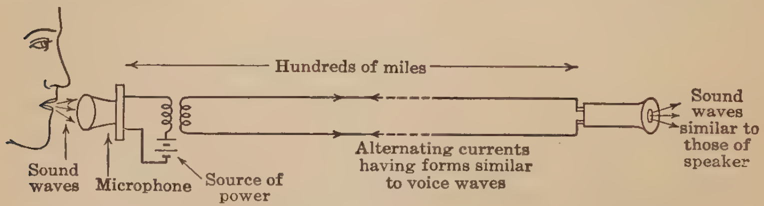

FIG. 1.—Indicating how the electromagnetic waves are guided along wires in the ordinary scheme of wire telephony.

ing; for example, for one telephone channel the amount of power used is about one-thousandth that required for a small incandescent light.

In the specific service which it is the purpose of this book to analyze an electric current is made to flow to and fro in a vertical wire (the transmitting antenna) about a million times per second. The strength of this current is made to increase or decrease in accordance with the voice of a speaker, or the complex sound waves from an orchestra. In another vertical wire (the receiving antenna) hundreds, or perhaps thousands, of miles away, corresponding currents are set up and, when properly amplified by the modern radio receiving set, give off a practically perfect reproduction of the voice or orchestra at the transmitting antenna, as suggested in Fig. 2. In this service there is no connecting wire between the sender and the receiver as there is in the ordinary telephone conversation and it was therefore originally called **wireless communication**; it is nowadays called **radio communication** or merely

radio. The power is *radiated* from the transmitting antenna, the same as heat and light are radiated from the sun; such radiated energy not only requires no connecting wires for its transmission, but actually travels better through a vacuum than it does through air.

In this book we shall analyze the elementary laws involved in the sending and receiving apparatus of the radio communication scheme, as well as the laws (in so far as they are known) governing the actual travel of the radiated energy. This will require a general review of the action of continuous and alternating currents and a special study of the action of very high-frequency alternating currents in so far as this differs from that of alternating currents of ordinary frequency. In the complete scheme of radio

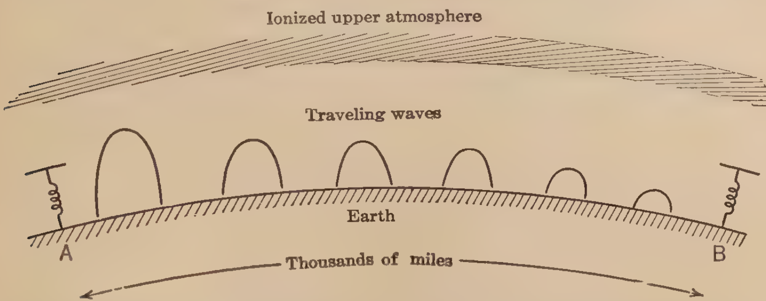

FIG. 2.—In radio communication the electromagnetic waves are shaken free from the antenna, and spread out and upward; their travel is generally confined to the hollow sphere between the earth's surface and the ionized atmosphere, about 150 miles above the earth's surface.

communication there are employed continuous currents and pulsating currents, as well as low- and high-frequency alternating currents; therefore we must have a rather comprehensive grasp of electric currents in general before we can understand radio.

2. Electrons.—It has been firmly established that every atom of matter is charged with minute particles of electricity, so-called *electrons*. An electron when detached from the atom of matter with which it is associated shows none of the properties of ordinary matter. It does not react chemically with other electrons to produce some new substance; moreover, all electrons are similar, no matter from what type of atom they have been extracted. Thus the electron from the hydrogen atom acts precisely the same as the electron from oxygen, iron, chlorine, or any other substance.

It seems that *the electron is nothing but electricity.* It is definite in amount, always being exactly the same, and is generally supposed to be the smallest possible quantity of electricity, i.e., electricity cannot be subdivided into quantities any smaller than the electron.

3. Modern View of the Electric Current.—It is now generally taken as a fact that an electric current is nothing but a moving electron, or electrons. The amount of electricity on one electron is so small that the current produced by one electron in motion cannot be detected by the finest current-measuring instrument, even the most sensitive. To produce currents of the magnitude occurring in every-day experience requires the motion of electrons measured in billions of billions per second.

An ordinary incandescent lamp requires a current of about one ampere; such a current requires that about 10^{19} (a number made up of 1 followed by nineteen ciphers) electrons flow past any point in the circuit each second. This large number per second might be brought about by a comparatively few electrons moving rapidly or by a great many moving more slowly. Contrary to what one might naturally think, the progressive motion of the electrons in a wire carrying current is very slow. To produce a current of one ampere in a copper wire one millimeter in diameter requires that the average velocity of the electrons be only about 0.001 cm. per second. This figure is based on the generally accepted assumption that in such a metal as copper there are about as many free electrons (not bound to any special atom) as there are atoms.

4. Velocity of Motion of the Electrons.—Although the progressive motion of the electrons is very slow, as indicated in the above statement, it must not be thought that the actual velocity of the electrons is small. If we assume the validity of certain theorems of molecular mechanics (the "equipartition of energy" concept, for example) and thus calculate the average velocity of the electrons in a copper wire, at ordinary temperature, we obtain a result of about 6×10^6 centimeters per second. That is, even if there is no current flowing in the wire the electrons have a haphazard motion, due to the thermal agitation of the atoms, which gives them on the average a velocity of about 25 miles a second.

Now when current flows through the copper wire, the required progressive velocity of the electrons is only a fraction of one centimeter a second; even with a current so large that the copper wire

is heated to the melting temperature, the velocity of drift of the electrons is less than one centimeter per second. Thus an accurate concept of the electric current in a conductor shows it to be an imperceptible *drift* of the electrons, which have, due to temperature effects, heterogeneous velocities millions of times as great as the velocity of drift.

The reason for the slow progressive motion of the electrons is to be seen in the tremendous number of collisions they have with the molecules of the metal. A given electron, acted upon by the potential gradient of the wire carrying current, accelerates very rapidly and would acquire tremendous velocities if it did not continually collide with the more massive atoms of the metal.

It might seem that the electrons would gain considerable net velocity along the conductor in spite of the numerous collisions with atoms, but such is not the fact. The mass of an atom or molecule is many thousand times as great as that of an electron; in copper, for example, the mass of the molecule is about one hundred thousand times as much as that of the electron. When a collision occurs, therefore, between an electron and a copper molecule, the electron rebounds from the molecule with practically the same velocity in the backward direction as the forward velocity it had before colliding with the molecule.

There are instances where the electron does not collide with molecules and here the electrons acquire very high velocities. Thus in the vacuum tube the electrons leave the heated filament and flow through the vacuous space to the plate of the tube. In this vacuous space there are practically no molecules to hinder the electron's flow and it attains a velocity, before striking the plate, frequently measured in *thousands of miles per second!*

5. Direct, or Continuous, Current.—In some circuits, as for example those used for electroplating, it is necessary that the electrons continually progress in the same direction around the circuit. The motors which drive trolley cars are another illustration of apparatus requiring the electrons to progress around the circuit continually in the same direction. The current required for charging a storage battery is of the same kind.

When the electric current consists of such a uniform, unidirectional motion of the electrons it is said to be a direct, or continuous, current. In the early art of electrical engineering practically all uses of electric power required continuous current, but

at present continuous current is used only in special cases. In radio circuits continuous current has been common for heating the filaments of the vacuum tubes (although at present alternating current is being used more and more) and is always required for the plate circuit of the vacuum tube. A continuous current supply is also always required for the so-called C battery circuit of a radio receiver.

6. Units of Current.—The common unit of current is the *ampere;* like all other standard quantities it has been fixed by international agreement, and is taken as that current which will electroplate silver at a certain rate. It suffices for the beginning student to know approximately the value of the ampere. Vacuum tubes designed for storage battery operation use about 0.25 ampere to heat their filaments. The ordinary 100-watt incandescent lamp uses about one ampere of current. The plate circuit of the ordinary vacuum tube uses about one-thousandth of one ampere; a current of this magnitude (0.001 ampere) is called one *milliampere.* Occasionally currents as small as one millionth of one ampere are used; such a current is called one *microampere.*

7. Method of Generating Continuous Current.—A device which generates electrical power must necessarily be one which changes energy from some other form into electrical energy. Energy itself cannot be generated. A device, then, which generates continuous current power must necessarily be a device which changes mechanical, chemical, or some other form of energy into electrical energy.

For small amounts of power batteries are extensively used. The ordinary " dry " battery is a combination of elements which changes chemical energy into electrical energy. If the battery is comprised of such elements that the energy change is reversible it is called a *storage* battery. Thus in radio we use dry batteries which, when used up, must be discarded. The zinc which has been consumed during the life of the battery cannot be efficiently restored. On the other hand, the well-known storage battery will efficiently absorb electric energy from some other source (generator or rectifying outfit) and afterward deliver it to the radio set. For larger amounts of power the direct current (or continuous current) generator, run by a steam engine or similar mover, must be used. In this case it is the chemical energy of the burning coal which develops the electrical energy.

8. Alternating Current.—Practically all applications of electric power in every-day life use alternating current; in such circuits the electrons in the wire flow first in one direction and then in the opposite direction. Such alternating current has marked advantage over direct current, especially where the customer is at appreciable distance from the power house.

In most of the power circuits in America the alternating current reverses its direction of flow one hundred and twenty times a second, that is, there are sixty complete cycles of reversal per second. The electrons flow in the wire in one direction for 1/120 of a second, then stop, reverse their flow and maintain this direction of flow for 1/120 of a second, then stop again and start to flow in the original direction.

The number of complete cycles of flow is called the **frequency** of the current; the above-mentioned case would be called a 60-cycle current, or we might say, the frequency of the current is 60.

The currents used in telephone conversations are alternating; the frequencies of these voice currents vary over a wide range. The vowel sounds have frequencies from perhaps 100 to 500, whereas the consonant frequencies reach as high as 5000 or more. The frequencies of the currents used to convey the music of an orchestra extend over about the same range as the voice, using somewhat lower frequencies in the bass notes, however. Thus for organ and orchestra music the frequency range extends even below 50 complete vibrations per second.

The frequency of currents used in the circuits of a radio transmitter or receiver are extremely high. For the ordinary transoceanic radio telegraphy the frequency is about twenty thousand cycles per second. It is customary to give radio frequencies in *kilocycles*, one kilocycle being one thousand cycles. Thus we would say that the frequency of the above-mentioned radio telegraphy current is 20 kilocycles.

The frequencies used by the broadcasting stations are about one million cycles, or 1000 kilocycles. Certain experimental radio channels are using frequencies as high as 20,000 kc. Difficult as it may seem to comprehend, the above statements are facts, and even more startling ones might be made. In the laboratory it has been possible to generate frequencies as high as 300,000 kc.; this means that the currents are reversing their direction of flow at the rate of 300,000,000 complete cycles per second!

9. Methods of Generating Alternating Current.—Alternating-current power cannot be generated by batteries; it is practically always (except for telephony and radio) generated by rotating machines driven by steam turbines. It is not possible to generate efficiently by rotating machines any frequencies above about 20 kc. In very special cases machines have been built to generate as high as 200 kc. but such are prohibitively expensive, difficult to maintain, and extremely inefficient.

The vacuum tube, properly arranged, will generate frequencies of the widest range imaginable. The same tube connected to one circuit will generate frequencies as low as one cycle per second and when put on another circuit will generate as high as 100,000,000 cycles per second.

As mentioned previously for continuous current, no device

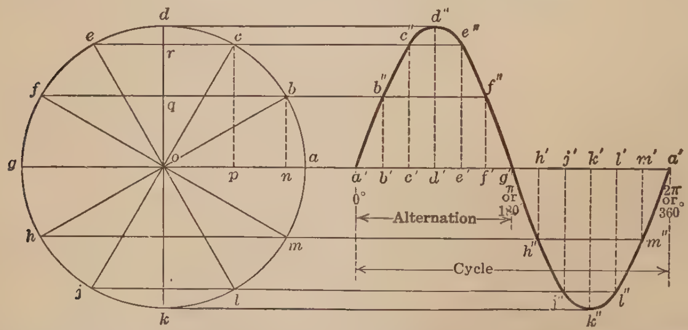

FIG. 3.—The sine wave form, ordinarily assumed for currents and voltages in alternating current circuits, is obtained from the projections, on one of the axes, of a uniformly rotating vector.

can *generate* alternating-current power; it merely converts energy from one form into another. In the case of the vacuum tube, some source of continuous current power is required; the vacuum tube changes a part of its continuous current power supply into alternating-current power.

10. Wave Form of Alternating Current.—The form of the alternating current generally assumed in alternating-current theory is that of a sine curve; the instantaneous value of the current is given by the height of the curve above or below the axis, and time is reckoned along the axis.

Such a curve is used for representing either a voltage or a current; in Fig. 3 is shown a voltage curve of sinusoidal (sine curve)

shape. The maximum value of the voltage is given by the symbol E_m and the frequency, or number of cycles per second is always given by the symbol f. The instantaneous value of the voltage is represented by e, so that the equation of such a voltage is then

$$e = E_m \sin 2\pi ft. \quad \ldots \ldots \ldots \quad (1)$$

As the expression $2\pi f$ occurs so frequently it is worth while to abbreviate it; the symbol ω is generally used in place of $2\pi f$, so that Eq. (1) becomes

$$e = E_m \sin \omega t.$$

In case a current is being considered its equation is evidently

$$i = I_m \sin \omega t.$$

in which i and I_m are the instantaneous and maximum values of the current, respectively.

11. Effective Value of a Sine Wave.—It is evident that the value of an alternating current or voltage is continually changing, taking successively all values between its positive maximum and negative maximum values. To speak of an alternating current as "so many amperes" obviously requires that some definite proportion of the maximum value be taken. This proportion is fixed by assuming that an alternating current has a value of one ampere when it produces heat at the same average rate as one ampere of continuous current, in flowing through a certain resistance such as the filament of an incandescent lamp. We can ascertain this proportionality factor either experimentally or theoretically; both give the same result. An alternating current of sine shape produces heat at the same average rate (through a certain resistance) as does one ampere of continuous current if the alternating current has a maximum value of $\sqrt{2}$ ampere. Such an alternating current is said to have an **effective value** of one ampere. From the relation we get the equation

$$I = I_m/\sqrt{2}, \quad \ldots \ldots \ldots \quad (2)$$

in which I is the value of alternating current in effective amperes.

If for example a sine wave of alternating current has a *maximum value* 100 milliamperes it is said to be a current of 70.7 milliamperes.

In the same way the effective value of an alternating voltage of sine shape is $\frac{1}{\sqrt{2}}$ of its maximum value. If the voltage acting in an antenna from a distant transmitting station is of sine-wave form and has a maximum value of 50 microvolts, it is specified as a signal strength of $\frac{50}{\sqrt{2}} = 35$ microvolts.

12. Distorted Waves.—Radio communication utilizes currents of greatly differing forms. In Fig. 4 are shown two current forms occurring continually in radio circuits. In *A* is shown the form

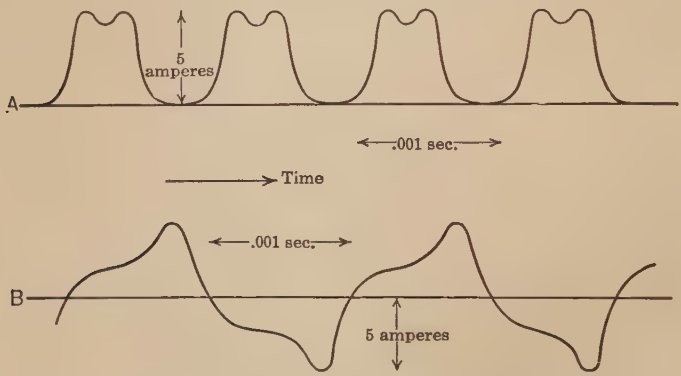

Fig. 4.—Two types of non-sinusoidal, or distorted, waves.

of plate current occurring in the plate circuit of a vacuum tube used for generating alternating current power and in *B* is shown the current wave through a loud speaker to represent a comparatively pure musical note. In *A* the current does not even reverse, as shown by the fact that it does not go below the zero line, and in *B* the curve is far from a sine wave. Complex as these currents may seem they must be thoroughly understood by any one who attempts even an elementary understanding of radio.

13. Composition of Distorted Waves.—A wave is said to be periodic if it repeats itself; evidently both of the complex waves of Fig. 4 are periodic. Now any periodic wave, no matter how complex its shape, is made up of a large number of pure sine waves, all acting at the same time. These different sine waves are not of the same frequency but have frequencies which are multiples of the lowest frequency. In case the wave has the appearance of

curve A (Fig. 4) it is composed of a certain amount of continuous current, in addition to a large number of sine waves. The magnitude of the continuous current component is given by the average height of the current curve, above the zero axis. In case the wave has the shape of curve B (Fig. 4) there is no continuous current component. This follows from the foregoing statement regarding the magnitude of the continuous current component; curve B has as much negative area (below the zero axis) as it has positive area (above the zero axis), hence the average height of curve B above the zero axis is zero.

Let us suppose that in Fig. 4 curve A, the time between successive pulses is 0.001 second, and that the maximum instantaneous value of the current is 5 amperes. Then the equation of this curve would be approximately

$$\begin{aligned} i = 1.5 &+ 2 \sin 2\pi 1{,}000t + 1.5 \sin 2\pi 2{,}000t \\ &+ 1.2 \sin 2\pi 3{,}000t + 0.9 \sin 2\pi 4{,}000t \\ &+ 0.7 \sin 2\pi 5{,}000t + \text{etc.} \quad \ldots \ldots \ldots \quad (3) \end{aligned}$$

The first term, 1.5, represents the continuous current component of the wave; the second term, $2 \sin 2\pi\, 1{,}000t$, is the **fundamental** alternating current with a frequency of 1,000 cycles. The third term, $1.5 \sin 2\pi\, 2{,}000t$, has twice the frequency of the fundamental and is called the **second harmonic**. The fourth term, $1.2 \sin 2\pi\, 3{,}000t$, has three times the frequency of the fundamental and is called the **third harmonic,** etc. The more complex the wave form the more harmonics there are in its makeup.

The wave form of curve B of Fig. 4 is a much simpler case of distortion than is that of curve A. It is closely representable by the equation

$$i = 3.5 \sin 2\pi 1{,}000t + 2 \sin (2\pi 3{,}000t - 30°) + 1 \sin 2\pi 5{,}000t. \quad (4)$$

This wave is then composed of a *fundamental* of 3.5 amperes, a *3rd harmonic* of 2 amperes, lagging 30° behind the fundamental, and a *5th harmonic* of 1 ampere. This wave has no continuous current component; its average value is zero, there being as much curve area above the axis as there is below. The two wave forms of Fig. 4 are evidently much distorted compared to the sine wave of Fig. 3 but they are very simple compared to the forms representing the voice and music of radio telephony.

14. Pulsating Current or Voltage.—The ordinary battery gives a continuous voltage so nearly constant in magnitude that the most sensitive instrument detects no change. A continuous current generator, on the other hand, gives a voltage which, while constant enough for operating motors, charging batteries, etc., has a fluctuation in magnitude which is readily detectable by various instruments. The fluctuation is of audible frequency and can often be heard over radio telephone channels as a high musical hum. For an ordinary generator the voltage equation might be

$$e = 110 + 1 \sin 2\pi 800t. \quad \ldots \ldots \quad (5)$$

The second term of the equation is referred to as the **commutation ripple** and it is this ripple which seriously interferes with the use

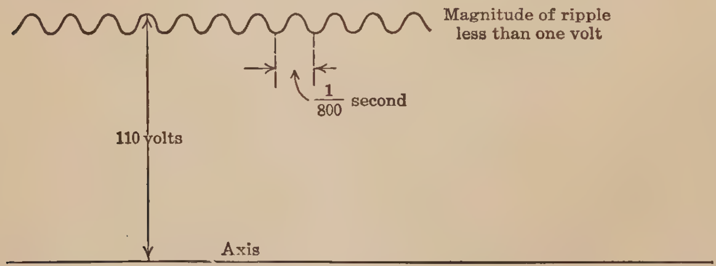

FIG. 5.—The voltage of even a continuous-current generator is not really uniform; it has slight pulsations called commutator ripples.

of direct-current power lines for operating a radio receiver. Such a voltage has about the appearance of Fig. 5. Such a voltage or current which is made up largely of a continuous component is said to be a **pulsating** voltage or current.

With the present-day tendency to rectify alternating-current power supply to obtain the power for operating radio sets the question of pulsating currents and voltage is of great importance. The alternating-current power from the house wiring has first to be rectified; this results in a pulsating current of the form shown in Fig. 6 *a*. By means of *filters* (see p. 248) the ripples are reduced in a series of steps so that the current as it goes through successive sections of the filter has the appearance of curves *b*, *c* and *d*. The filters do not oppose the flow of the steady component of the current (curve *d*) but do impede greatly the passage of the alternating components of the current (the ripples of curves *a*, *b* and *c*).

Later in the chapter we shall show how filters accomplish this separation of the continuous and alternating components of a wave.

15. Voltage and How Produced.—Currents always flow in electrical circuits under the action of some electric pressure; there must be somewhere in the circuit a device which is generating, or setting up, this pressure. This electric pressure which causes the electrons to flow along the conductor (that is, produce an electric

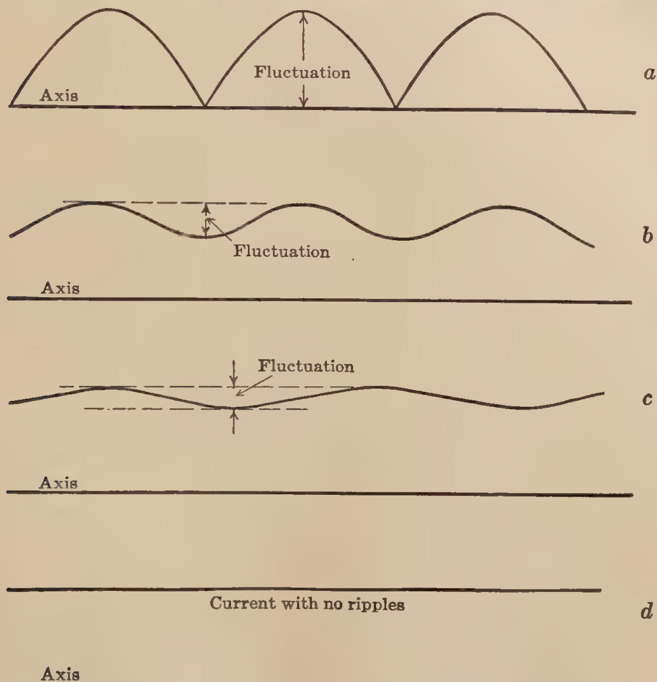

Fig. 6.—A current, pulsatory even as much as that in curve *a*, can be smoothed out by filters as suggested in the successive curves.

current) is generally said to be a **voltage,** or **electromotive force,** and is measured in **volts.** In just this same way water is caused to flow in pipes by some device which generates a pressure; thus the centrifugal pump of a fire engine corresponds to the voltage-generating device of the electric circuit. In the electric circuit we have practically only two methods of generating electromotive force or voltage, the generator and the battery. There are some other methods of generating voltage but they are of comparatively little importance.

There are generators which are so built that they develop a voltage always in the same direction and practically constant in magnitude; such a machine is called a **direct-current**, or **continuous-current**, generator. It is always equipped with a **commutator** on which brushes make contact for connecting the revolving armature (the seat of the voltage) with the external circuit. As indicated in Fig. 5, such generators do not develop a really continuous voltage; there is always a slight irregularity, the commutation ripple, which must be filtered out if the power of the generator is to be used for operating a radio receiver or transmitter.

There is another type of generator called an **alternator** which generates a voltage continually reversing in direction, just like the wave depicted in Fig. 3. An alternator generally has a stationary armature, the field poles revolving. The frequency of reversal of the voltage (or simply frequency) in general American practice is either 60 cycles per second or 25 cycles per second. The power supplied to houses for lighting purposes is nearly always 60-cycle current.

In addition to these two types of generators for producing an electric pressure, or voltage, there is available the battery, which utilizes a chemical action to maintain a voltage. We may use either a **primary battery** which utilizes an irreversible chemical cycle to set up its electric pressure, or the **storage battery** which utilizes a reversible chemical cycle in developing its voltage. Both types of battery generate an extremely constant voltage, it being so constant that the very finest electrical instruments can detect no fluctuations. To be sure as the battery delivers energy to its connected load its voltage gradually falls, but the fall is so slow and uniform that for any short period of time the battery may be considered as a source of constant voltage, or electromotive force.

16. Batteries.—The ordinary dry cell utilizes zinc and carbon as its two electrodes and a solution of salammoniac as its electrolyte. As the electrolyte is generally contained in a mass of inert absorbent material, instead of occurring as free liquid, this type of cell is known as the *dry cell.* It really is not dry at all; if it were it would show no electromotive force and would be useless. The zinc is gradually used up as the dry cell is used, and in a very old cell holes occur in the zinc (which is in the form of a containing can for the rest of the cell) where it has been completely "eaten

up" by the chemical action of the salammoniac. The ordinary dry cell develops about 1.5 volts when new; this is the same irrespective of the size of the cell. Thus the 6-inch dry cells used for filament supply give the same voltage as the tiny B battery dry cells. The large cells can deliver more current, for a longer time, than the small cells but the voltage is the same for each.

The ordinary storage cell uses lead plates covered with some lead salts, for the two electrodes and a sulphuric acid solution for the electrolyte. Such a combination is capable of receiving a charge when connected to a suitable power supply and of delivering this charge (or about 80 per cent of it) to a radio set or other device. Each cell of such a lead battery may consist of many plates instead of just two, but no matter how numerous the plates they are connected up in two sets. The number of plates per set and their size are determined by the number of ampere-hours the battery is to deliver. A lead cell when fully charged generates about 2.2 volts; this pressure gradually falls as the charge is used up until, just before the cell is ready for a new charge, the voltage is about 1.8 volts. The ordinary lead storage battery used for supplying power to a radio set will deliver about 100 ampere-hours before requiring a new charge. Thus if 2 amperes are required for a radio set the battery should run for 50 hours before requiring a re-charge.

It costs a great deal more to get power from batteries than it does from a lighting company's power supply. Thus a 6-inch dry cell will deliver about 20 watt-hours and costs about $0.40; at this rate it would cost $20 for one kilowatt-hour of energy from dry cells whereas this same amount of energy could be bought from a power company for $0.10. The advantage of the batteries lies in their portability, constancy of voltage, and ease with which a voltage of any desired value may be obtained by connecting cells in series, etc.

When much power is to be obtained for a radio set it becomes prohibitive to use batteries, however, because of the excessive expense. Thus some radio sets require as much as 350 volts to operate their output tubes and this amount cannot economically be obtained from batteries; the power supply of the house must be utilized in such cases. But as the house supply is alternating current and as continuous current is required for the radio set some means must be devised to change the alternating-current power into continuous current power.

17. Rectifiers.—Whereas it is generally good engineering to use an alternating-current motor running a continuous-current generator to obtain the desired constant voltage this is not practicable for such small amounts of power as are required for the average receiving set; the cost is prohibitive.

An electric valve of some kind is usually employed to rectify the alternating-current supply. There are several types of such valves used today all of which operate in fundamentally the same fashion; for a given magnitude of impressed voltage they pass more current in one direction than in the other. A perfect valve would pass no current at all in the undesired direction but most valves do pass a small amount of so-called reverse current.

The *mercury arc rectifier* of Cooper Hewitt uses a glass tube filled with mercury vapor having as its two electrodes graphite and liquid mercury. In operation the glass bulb is filled with the characteristic green glow of ionized (conducting) mercury vapor and a small white-hot spot in the pool of mercury indicates the place where the current enters the mercury electrode. Such rectifiers pass many amperes of current when the mercury is negative and practically none when the mercury is positive.

The *liquid rectifier* may use various electrolytes and electrodes, but those commonly employed are lead and aluminum for electrodes and boric acid for electrolyte. There is a slight reversed current in such rectifiers and they cannot carry much current. Such rectifiers are generally used as so-called **trickle chargers** for storage batteries.

A practically perfect rectifier utilizes a hot and cold electrode in an evacuated vessel; it is called a *diode.* The hot electrode is generally a tungsten filament heated to incandescence by an electric current and the cold electrode a metallic plate close to, or surrounding, the heated filament. This type of valve passes no reversed current even if the reversed voltage is hundreds or thousands of volts; when the plate is positive a current of an ampere or more may flow, the magnitude of this current depending upon the size and temperature of the filament. This type of rectifier is used extensively in the power supply apparatus for modern radio receivers; it will be further discussed in chapter IV.

A slightly modified form of the *vacuum valve* utilizes the same elements but the enclosing vessel contains an inert gas at a pressure about half that of the atmosphere. The effect of the inert

gas is to increase the amount of rectified current, for a given plate voltage and filament size. This gas type of valve (of which the *Tungar* is an example) will not stand as much reversed voltage as the vacuum valve but in many cases this is of no importance. In another type of gas valve no hot filament at all is used. A comparatively low gas pressure is used and the valve rectifies as a consequence of the peculiar shape of its two cold electrodes.

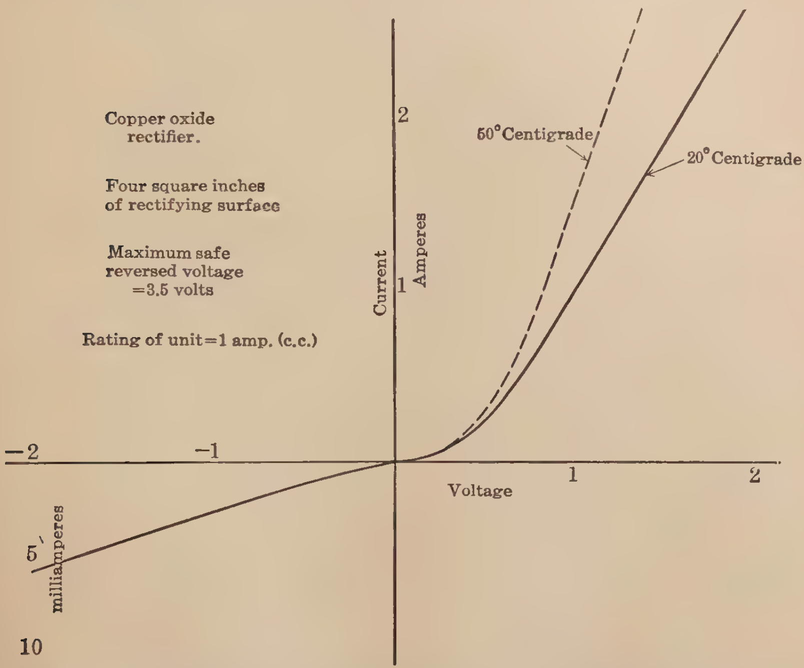

Fig. 7.—A rectifier carries current more readily in one direction than in the other; this curve shows the performance of a copper-copper oxide rectifier.

One of the more recent rectifiers utilizes an oxide of copper coating on a copper plate. Across the junction of this oxide and copper, current flows readily in one direction and practically none flows in the reverse direction until the reversed voltage is several volts. Such *copper oxide rectifiers*, although in the experimental stage at present, seem likely to prove of much importance in the future.

In Fig. 7 is shown a typical curve of the performance of a rectifier; this one is for a copper oxide retifier having about 4 square

inches of rectifying surface. The safe current is limited by heating; if too much current is drawn through the rectifier it becomes too hot and the oxide will crack off from the copper and the rectifier is spoiled.

These various rectifiers change alternating current into pulsating direct current; to smooth out the fluctuation, filters (see p. 249) must be used between the rectifiers and the radio set.

18. Current Flow in a Continuous Current Circuit.—When a battery or other source of continuous voltage is connected to a **closed circuit,** such as a coil of wire, incandescent lamp, filament of a vacuum tube, etc., a continuous current will flow, and the magnitude of the current is determined by the amount of voltage, and the resistance of the circuit. By a closed circuit is meant one in which the two terminals, or poles, of the source of e.m.f. are joined by a continuous circuit of conducting material. In general the circuit will be a continuous path of metallic conductor, but in certain cases, such as a storage battery, part of the closed circuit consists of a conducting liquid. Contrasted to a closed circuit we have the **open circuit** in which the continuous conducting path is interrupted by some insulating material. Thus the filament circuit of the ordinary radio receiver is a *closed circuit* when the filaments are lighted; when the filament switch is opened the air separating the two metallic contacts of the switch prevents current flow and so the circuit is open.

Frequently the transformers of a radio receiver become *open circuited;* the fine wire of which the coils are made breaks and the minute air gap thus formed between the two broken ends prevents current flow and so the winding changes from a closed circuit to an open circuit.

The amount of current which flows in a closed circuit depends upon the voltage impressed and the resistance of the path. The filament of the ordinary vacuum tube is designed for a 6-volt circuit; if a battery of three storage cells in series is connected to the filament it operates satisfactorily. However if, as sometimes happens, the B battery of the radio receiver is connected to the filament circuit, the filament is heated to such an extent that it volatilizes, in a small fraction of a second. The voltage of the B battery is several times as large as that for which the filament is designed; too much current flows and the filament is burned out.

Even when the same voltage is used different circuits draw different amounts of current. Thus if a 4-volt supply is connected to the filament of a 199 type of tube about 0.06 ampere will flow, whereas if the filament of a type 201-A tube is connected to the 4-volt supply about 0.20 ampere will flow. This is because the resistance of the type 201 filament is much lower than that of the other.

19. Resistance.—The resistance of a circuit depends upon what material the circuit is composed of, its length, and its cross-section. In general, metals offer much lower resistance than any other substances; silver and copper offer lower resistance than any of the other metals. Of these two, silver has the lower resistance but as the copper is so much cheaper it is almost universally used in electrical apparatus.

Tungsten has a resistance about four times as great as that of copper; it is used for the filaments of vacuum tubes primarily because it does not melt or evaporate appreciably at the high temperatures required for filament operation. Sulphuric acid solution such as is used in storage batteries has a resistance about one million times as great as that of copper; to keep the resistance of such a battery reasonably low, therefore, the length of path through the solution from positive to negative plate must be small, and the cross-sectional area of the solution must be large. Both of these conditions are satisfied in the ordinary battery; as a result the resistance of the path through the acid solution is much less than one *ohm*, the unit of resistance.

To control the current through the filament of a vacuum tube an extra adjustable resistance is connected in series with it; by increasing the amount of this added resistance the filament current is cut down. This extra resistance has a sliding contact by means of which more or less of the resistance is introduced in the circuit; it is generally called a *rheostat*. As a rheostat performs its function solely by virtue of its resistance, the wire of which it is made is generally some high resistance metal; certain alloys of copper and nickel are generally used, having a resistance about twenty times as great as that of an equal-sized copper wire.

The resistance of a conductor is expressed by the formula

$$R = \rho\frac{l}{a}, \quad \ldots \ldots \ldots \quad (6)$$

in which l = length of conductor;
a = cross-section of the conductor;
ρ = a constant depending for its value upon the metal used; and
R = the resistance.

In American practice l is generally measured in feet, a is measured in circular mils, and ρ is given in *ohms per mil-foot.* A circular mil is the area of a circle 0.001 inch in diameter. The resistance of copper per mil-foot is about 10.5 ohms. This is the figure for ordinary temperature; it increases about 1 per cent for every four degrees (Fahrenheit) rise in temperature.

As an illustration of the use of this formula we will calculate the resistance of the secondary winding of an amplifying transformer wound with 10,000 turns of copper wire 0.005 inch in diameter, the average length of one turn being 6 inches.

As the area of a circle varies with the square of the diameter, this wire has a cross-section of 25 circular mils, its total length is 5,000 feet. Then

$$R = 10.5 \times \frac{5{,}000}{25} = 2{,}100 \text{ ohms.}$$

The copper wire used in American practice is made in a series of sizes which are determined by the Brown and Sharpe gage. The sizes, cross-sections, and resistances of the various wires made in accordance with this gage are given in the table on next page.

20. Ohm's Law.—This is the name given to the law which relates the resistance, the voltage, and the current flowing in a circuit. If E is the voltage impressed on the circuit, R is its resistance, the current I is given by the relation

$$I = \frac{E}{R}. \qquad (7)$$

If I is to be given in amperes, E must be given in volts when R is given in ohms. As an illustration of the application of this law let us calculate how much current would flow in the transformer winding above if a 45-volt battery is connected to its terminals.

$$I = \frac{45}{2{,}100} = 0.0214 \text{ ampere.}$$

TABLE I *

SOLID COPPER WIRE—AMERICAN WIRE GAGE

100 Per Cent Conductivity; Density 8.89 at 20° C.

Gage No.	Diameter in mils	Cross-section		Resistance at 20° C. or 68° F.†		Weight in Pounds		Feet per Pound
		Circular Mils	Square Inch	Ohms per 1000 Feet	Ohms Per Mile	Per 1000 Feet	Per Mile	
0000	460.0	211,600	0.1662	0.04901	0.259	640.5	3380	1.561
000	409.6	167,800	0.1318	0.06180	0.326	507.9	2680	1.968
00	364.8	133,100	0.1045	0.07793	0.411	402.8	2130	2.482
0	324.9	105,500	0.08289	0.09827	0.519	319.5	1680	3.130
1	289.3	83,690	0.06573	0.1239	0.654	253.3	1340	3.947
2	257.6	66,370	0.05213	0.1563	0.825	200.9	1060	4.977
3	229.4	52,640	0.04134	0.1970	1.04	159.3	841	6.276
4	204.3	41,740	0.03278	0.2485	1.31	126.4	667	7.914
5	181.9	33,100	0.02600	0.3133	1.65	100.2	529	9.980
6	162.0	26,250	0.02062	0.3951	2.09	79.46	420	12.58
7	144.3	20,820	0.01635	0.4982	2.63	63.02	333	15.87
8	128.5	16,510	0.01297	0.6282	3.32	49.98	264	20.01
10	101.9	10,380	0.008155	0.9989	5.28	31.43	166	31.82
12	80.81	6,530	0.005129	1.588	8.38	19.77	104	50.59
14	64.08	4,107	0.003225	2.525	13.3	12.43	63.3	80.44
15	57.07	3,257	0.002558	3.184	16.8	9.858	52.0	101.4
16	50.82	2,583	0.002028	4.015	21.2	7.818	41.3	127.9
17	45.26	2,048	0.001609	5.064	26.7	6.200	32.7	161.3
18	40.30	1,624	0.001276	6.385	33.7	4.917	26.0	203.4
19	35.89	1,288	0.001012	8.051	42.5	3.899	20.6	256.5
20	31.96	1,022	0.0008023	10.15	53.6	3.092	16.3	323.4
21	28.46	810.1	0.0006363	12.80	67.6	2.452	12.9	407.8
22	25.35	642.4	0.0005046	16.14	85.2	1.945	10.3	514.2
23	22.57	509.5	0.0004002	20.36	108	1.542	8.14	648.4
24	20.10	404.0	0.0003173	25.67	135	1.223	6.46	817.7
25	17.90	320.4	0.0002517	32.37	171	0.9699	5.12	1,031
26	15.94	254.1	0.0001996	40.82	216	0.7692	4.06	1,300
27	14.20	201.5	0.0001583	51.46	272	0.6100	3.22	1,639
28	12.64	159.8	0.0001255	64.90	343	0.4837	2.55	2,067
29	11.26	126.7	0.00009953	81.84	432	0.3836	2.03	2,607
30	10.03	100.5	0.00007894	103.2	545	0.3042	1.61	3,287
31	8.928	79.70	0.00006260	130.1	687	0.2413	1.27	4,145
32	7.950	63.21	0.00004964	164.1	866	0.1913	1.01	5,227
33	7.080	50.13	0.00003937	206.9	1090	0.1517	0.814	6,591
34	6.305	39.75	0.00003122	260.9	1380	0.1203	0.635	8,310
35	5.615	31.52	0.00002476	329.0	1740	0.09542	0.504	10,480
36	5.000	25.00	0.00001964	414.8	2190	0.07568	0.400	13,210
38	3.965	15.72	0.00001235	659.6	3480	0.04759	0.251	21,010
40	3.145	9.888	0.000007766	1049	5540	0.02993	0.158	33,410

* Reproduced from Pender's Handbook for Electrical Engineers, 1922.

† Let C = per cent conductivity, R_{20} = resistance of 100 per cent conductivity wire at 20° C. (from table), R_t = resistance of wire of conductivity C at any temperature t° C., then

$$R_t = R_{20}\left[\frac{100}{C} + 0.00393(t-20)\right].$$

As radio circuits generally use but small currents in many cases it is customary to use as the unit of current the **milliampere** (one thousandth of one ampere), frequently abbreviated to **mil.** Thus we might say for the above case that the transformer winding draws 21.4 mils from its battery.

A certain filament has a resistance of 5 ohms when at room temperature and 20 ohms when red-hot. A 6-volt battery makes it burn red. How much current does it draw from the battery when the switch is first closed and how much after it has reached a red heat?

$$\text{Starting current} = \tfrac{6}{5} = 1.2 \text{ amperes}$$

$$\text{Operating current} = \tfrac{6}{20} = 0.3 \text{ ampere}$$

21. Ampere-Hours.—The **ampere-hour** is one of the compound electrical units which has much significance for the owner of a battery-operated radio receiver. Either a storage battery or a dry battery will give out after being connected to its circuit a certain length of time; the storage cell may be re-charged but the dry cell must be discarded as it is impossible to re-charge such batteries. If one experiments with batteries under different conditions it will be found that the more tubes a battery supplies the shorter the time it will last. Thus a storage battery which furnishes filament current for a three-tube set for 80 hours before requiring a re-charge will operate a seven-tube set only about 30 hours. The three-tube set draws a current of 0.75 ampere for 80 hours; this means that the battery is capable of delivering $80 \times 0.75 = 60$ ampere-hours. The seven-tube set requires 1.75 amperes for its filament supply; so that the number of hours this battery will last is given by the equation, time $= \dfrac{\text{ampere hours}}{\text{amperes}}$, or $\dfrac{60}{1.75} = 34$ hours.

The number of ampere-hours a cell is capable of delivering depends primarily upon its size; thus a storage battery to deliver 120 ampere-hours will weigh practically twice as much as one designed to give 60 ampere-hours per charge. The average 6-inch dry cell, such as is used for lighting filaments of the 199 type of tube, has a life of about 15 ampere-hours. The small cells used for B batteries have of course much less capacity. The $22\frac{1}{2}$-volt battery weighing 5 lb. has about 2 ampere-hours' life under aver-

age conditions, whereas the smaller type weighing 2 lb. has only 0.8 ampere-hour under the same conditions.

The number of ampere-hours available from a dry cell depends to some extent upon how many tubes are being operated from it. In Fig. 8 are shown curves for typical B batteries; it can be seen that the available ampere-hour increases as the current taken is decreased. Thus the 2-lb. battery, delivering 5 milliamperes, will last for 1000 milliampere-hours and when delivering 50 milliamperes will last for only 200 milliampere-hours. This means that

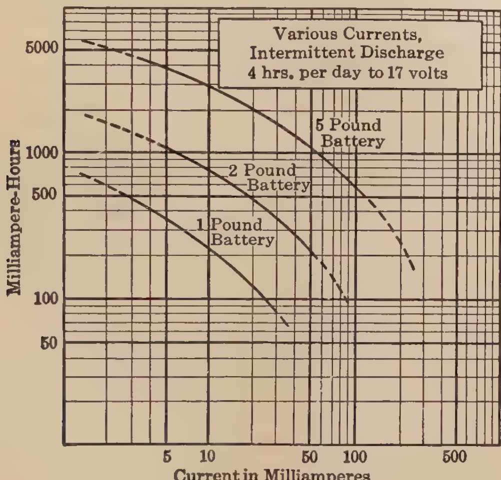

FIG. 8.—Showing the performance of small dry cells such as used for the plate circuits of radio sets. The ampere-hours obtainable before exhaustion diminishes as the rate of discharge becomes greater.

when delivering 50 milliamperes (an overload for a battery of this size) the battery is used up in 4 hours and when delivering only 5 milliamperes it will last 200 hours.

22. Power and Energy.—The rate at which a battery is delivering electrical energy to a device, such as a radio receiver, is generally measured in **watts.** When one ampere of current flows from a device generating one volt of electromotive force, energy is being used up at the rate of one watt. If the voltage source is developing 100 volts pressure and is delivering 5 amperes a power of 500 watts is being exerted. When a 90-volt battery is delivering 20 milliamperes of current to the plate circuit of a receiver the power

used is 1.8 watts. When a 6-volt storage battery is supplying 1.75 amperes to the filament circuit of a seven-tube radio receiver the power supplied to the filament circuit is 10.5 watts. A tube of the 199 type uses 0.06 ampere in its filament at 3 volts; the power used for heating this filament is 0.18 watt.

In a continuous current circuit, as in the examples given above, the power is obtained by taking the product of the current in amperes, by the electromotive force in volts—that is

$$\text{Power} = EI = I^2R, \quad \ldots \ldots \ldots \quad (8)$$

power being given in watts, E in volts, I in amperes, and R in ohms.

Frequently the watt is too small a unit to be conveniently used; the *kilowatt* is then employed. The milliwatt (one-thousandth of one watt) is frequently used in radio calculations.

The electrical units of power are frequently used when the energy is in forms other than electrical. Thus one speaks of energy given off in the form of sound; the rate at which energy is given off as sound may conveniently be expressed in electrical units. The average speaking voice gives off sound energy at the rate of about 10 microwatts.

When power is exerted for a certain duration of time *energy* is expended, or *work* is done. Thus if the lights in a house require 1 kilowatt of power for their operation they use in each hour one kilowatt-hour of energy. If the lights are used for six hours a day, six kilowatt-hours of work are expended.

If one watt of power is exerted for a time of one second then one **watt-second** of work is done. The watt-second is frequently called the **joule.** Thus a 6-volt battery delivering 2 amperes of current is furnishing each second 12 watt-seconds or 12 joules of energy. The ordinary speaking voice uses each second about 10 **microjoules** as sound energy.

From these examples it is seen that

$$\text{Energy} = EIt, \quad \ldots \ldots \ldots \quad (9)$$

and if E is in volts, I in amperes, and t in seconds, the energy is given in watt-seconds or joules.

The ordinary 6-inch dry cell will deliver 0.1 ampere for about 200 hours, and the average voltage of the cell during the discharge

is 1.3 volts. This represents the available electric energy there is in the cell. Evidently it is equal to

$$\text{Energy} = 1.3 \times 0.1 \times 200 \times 3600 = 93{,}600 \text{ joules.}$$

Fig. 8 shows that a 5-lb. B battery will deliver about 3 ampere-hours, when the discharge rate is 10 milliamperes. As the initial voltage is 22.5 and the final voltage 17 (see legend on figure), the average voltage is about 20. The energy is therefore $20 \times 3 \times 3600 = 216{,}000$ joules. This is about 160,000 ft.-lb. As the battery weighs 5 lb. it is evident that this type of dry cell contains sufficient stored electrical energy to lift itself 16,000 feet high, this on the assumption that the efficiency of the lifting motor, to which the energy is supplied, is 50 per cent.

A fully charged storage cell, of either the lead or Edison type, has about the same amount of stored electrical energy per pound of weight as have the dry cells analyzed above.

23. Current Flow in Alternating Current Circuit.—When an alternating voltage is impressed upon a circuit an alternating current will flow, and the frequency of this current will be just the same as that of the impressed voltage. In general the form of the current will be somewhat different from that of the voltage, unless this is a pure sine wave. In case the voltage is not a sine wave, but perhaps has ripples in it (see Fig. 4) then the ripples in the current may be less pronounced or they may be greatly exaggerated compared to the voltage ripples, depending upon the type of circuit.

It happens in many circuits that the current form differs greatly from a sine wave even though the voltage has a pure sine form; such circuits quite frequently occur in radio practice so they are taken up in a separate section later.

The amount of current which flows in a given circuit, with a given magnitude of impressed voltage, is generally different for alternating than for continuous current. There are a few exceptions to this rule, as for example the ordinary incandescent lamp. Suppose a 100-volt, 100-watt lamp; with 100 volts (c.c.) impressed, 1 ampere (c.c.) will flow; and with 100 volts (a.c.) impressed, 1 ampere (a.c.) will flow.

But consider the ringing circuit of the ordinary telephone line. With alternating voltage impressed, sufficient current flows in the circuit to ring the bell, but if a continuous voltage is impressed no

current flows. The circuit is an "open circuit" for continuous current

In many other circuits, however, the amount of continuous current is much greater than is the alternating current, for the same magnitude of voltage. One of the coils in a radio receiver, for example, may carry 0.01 ampere when one volt, of radio frequency, is applied, whereas when one volt of continuous voltage is impressed on the coil, one ampere flows.

24. Coils and Inductance.—In a continuous current circuit the only factor which limits the current in magnitude is the resistance. A coil of 5 ohms resistance, for example, when connected to a 10-volt battery will carry 2 amperes of current. If connected to an alternating-current generator, adjusted to give 10 volts, the current flowing may be only a fraction of one ampere. It is then evident that there is some feature of this circuit which acts differently toward alternating than toward continuous current.

In addition to its resistance such a coil possesses **inductance,** which characteristic does not interfere at all with the flow of continuous current but does very materially limit the alternating current.

The unit of inductance is the **henry**. This unit is sometimes too large for convenience so the millihenry (0.001 henry) and the microhenry (0.000,001 henry) are frequently used. As illustrations of the significance of these units we may note that the coils, used in connection with tuning condensers, in the ordinary radio receiver have an inductance of about 200 microhenrys.

The iron core coil used in the "filters" of a modern radio set have as much as 50 to 100 henrys of inductance. In the ordinary head phone there are two small coils made of many turns of fine wire. These coils have about one henry of inductance in the average phone.

25. Examples of Inductances.—The air core coils used in radio sets or for laboratory tests at radio frequencies have comparatively small values of inductance, both because of the few turns of wire used and the absence of an iron core. In Fig. 9 is shown a laboratory coil suitable for use at 500,000 cycles or less. Its size can be estimated from the ruler leaning against it. In Fig. 10 is shown a coil of 1500 turns of large wire; it is used in the laboratory for tests at about 100 cycles. At radio frequencies, such large coils cannot be used because they act like condensers (see p. 58)

instead of coils. In Fig. 11 is shown a view of one receiver of the ordinary head telephone; the diaphragm has been removed so

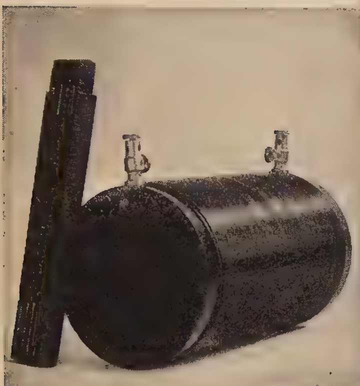

Fig. 9.

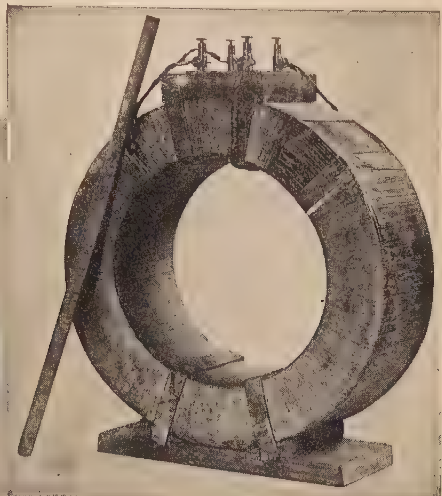

Fig. 10.

FIG. 9.—A single layer solenoid, being about 4 inches in diameter and 8 inches long, having 130 turns, has an inductance of 1100 microhenrys.

FIG. 10.—This large coil having 30 layers of No. 10 wire, 50 turns per layer, has a resistance of 10 ohms and an inductance of about 0.6 henry.

that the small electro-magnets may be seen. Although this pair of small coils have about one-thousandth of the weight of the coil

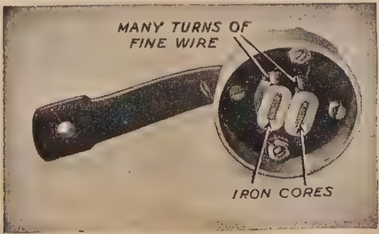

FIG. 11.—The small magnets inside an ordinary telephone receiver, such as used in radio sets, have many thousands of turns of very fine wire; the coils are wound on soft iron cores. Such a receiver has a continuous current resistance of about 1000 ohms and an inductance of about one henry.

shown in Fig. 10 they have a greater inductance due to the greater number of turns and the use of iron cores.

26. Inductive Reactance.—As mentioned above, a coil by virtue of its inductance, tends to limit the amount of current which an alternating voltage can send through it. Experiment shows that a given coil, having a certain fixed inductance, will impede the flow of current more for a high- than for a low-frequency current. Thus with 110 volts of 60-cycle frequency impressed, a certain coil passes 5 amperes of current, but when the same coil is connected to a 110-volt 500-cycle alternator only one ampere of current flows. We conclude therefore that the tendency of a coil to limit the current flow depends upon both its inductance and the frequency of the current. This combined effect of frequency and inductance is called **reactance;** we say that a coil limits the flow of alternating current because of its reactance. The magnitude of this reactance is proportional to the frequency, and to the magnitude of the inductance; in ohms the reactance is equal to $2\pi fL$, in which f is the frequency in cycles per second, and L is the inductance in henrys.

It is possible to have electric circuits which have practically no inductance, hence no reactance; an incandescent lamp is such a circuit. Here the alternating current is limited only by the resistance of the circuit. On the other hand, it is impossible to have a circuit having inductance which has no resistance. Coils always consist of many turns of wire and of course wire has resistance, hence a circuit having reactance always has resistance. It will, however, be shown later that in many radio circuits the resistance is so small compared to the reactance that it may be neglected in some calculations.

27. Calculation of Inductance.—There are a few simple forms of coils for which the inductance (or **coefficient of self-induction** as it is properly called) can be accurately calculated. Accurate formulas for the single circular turn and the toroid (doughnut-shaped coil) have been calculated, and for the cylindrical-shaped coil, or solenoid, tables of suitable factors have been compiled from which the inductance can be calculated closely enough for ordinary work.

If the coil has an iron core it is impossible to calculate its inductance accurately because the permeability of the iron changes with different values of current. For coils having completely closed magnetic circuits of iron with a known number of turns and current (that is a known number of ampere-turns) the flux in the magnetic

circuit can be calculated from curves furnished by the manufacturer of the iron and in this way the inductance is arrived at. It will be different, however, for every different current through the coil.

For a single circular turn of round wire

$$L = 4\pi R\left[\left(1 + \frac{r^2}{8R^2}\right)\log\frac{8R}{r} + \frac{r^2}{24R^2} - 1.75\right] \text{cm.}, \quad (10)$$

in which R = radius of turn, in centimeters, to center of wire;
r = radius of the wire;
log = logarithm to the base e.

This formula gives the inductance in centimeters; to get microhenrys divide the value obtained from the formula by 1000.

For a single-layer solenoid

$$L = 4\pi^2 R^2 n_1{}^2 l K \text{ cm.}, \quad (11)$$

in which R = radius of coil, to center of wire;
n = number of turns per centimeter of length of coil;
l = length of winding in centimeters;
K = a certain constant, depending upon the ratio of the coil diameter to its length. It is called Nagaoka's constant, and is given in the table on next page.

In the case of an iron core coil, such as the winding of a transformer, the method of calculating the inductance depends upon how the iron manufacturer furnishes the requisite data. If he gives a curve showing the flux density of the iron for different magnetizing forces the inductance is calculated as follows: Knowing the number of turns and current supposed to be flowing, and the length of the magnetic path in the iron, the *ampere-turns per centimeter of length of the iron* are calculated. From the magnetization curve the flux density is found. From this density and the cross-sectional area of the iron core the total flux in the core is obtained. Multiplying this flux by the number of turns in the coil gives the interlinkages. Dividing this by the assumed current gives the interlinkage per ampere. Dividing this value by 10^8 gives the number of henrys of self-induction.

TABLE II

$\frac{\text{Diameter}}{\text{Length}}$	K	$\frac{\text{Diameter}}{\text{Length}}$	K
0.00	1.000	0.95	0.700
0.05	0.979	1.00	0.688
0.10	0.959	1.10	0.667
0.15	0.939	1.20	0.648
0.20	0.920	1.40	0.611
0.25	0.902	1.60	0.580
0.30	0.884	1.80	0.551
0.35	0.867	2.00	0.526
0.40	0.850	2.50	0.472
0.45	0.834	3.00	0.429
0.50	0.818	3.50	0.394
0.55	0.803	4.00	0.365
0.60	0.789	4.50	0.341
0.65	0.775	5.00	0.320
0.70	0.761	6.00	0.285
0.75	0.748	7.00	0.258
0.80	0.735	8.00	0.237
0.85	0.723	9.00	0.219
0.90	0.711	10.00	0.203

Such a calculation gives the inductance of the coil for the assumed value of continuous current; the value for alternating current will generally be much lower and can only be found experimentally.

28. Inductance of Iron Core Transformers.—In all radio receivers iron core transformers are used, with their primary winding connected in the plate circuit of a vacuum tube. The plate current of the tube is thus flowing through the winding and the radio designer needs to know what value of self-induction the primary winding has *for alternating current* when the continuous current (plate current) of the tube is also magnetizing the core. The answer to such a question can only be obtained experimentally. It is found that the self-inductance for the alternating current decreases as the plate current of the tube increases, more for some grades of iron than for others. A typical curve showing the behavior of iron under this condition is given in Fig. 12. A few turns of wire were wound on the iron core and the inductance was

measured for an alternating current of 1000-cycle frequency, as various values of continuous current were passed through another winding on the same core. It is seen that the alternating-current inductance decreased rapidly as the continuous magnetization was increased.

This idea is of extreme importance in the choke coils used in *filters;* such coils are to choke out, or suppress, the alternating components of the rectified alternating current. Frequently the

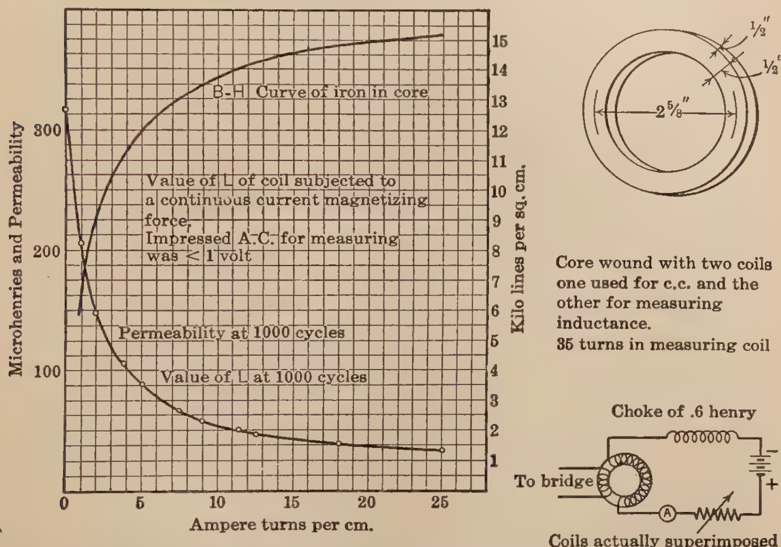

Fig. 12.—An iron core coil has an inductance, for alternating currents, which diminishes as its continuous current magnetization is increased; this represents the condition under which the transformer of an audio frequency amplifier operates.

rectified current, flowing through the windings, so magnetizes the core that the choking effect on the alternating components, or ripples, of the current is only a small fraction of what it should be.

29. Current Flow in Inductive Circuit.—If we consider a coil having a resistance very low compared to its reactance, the current, I, flowing through it, when an electromotive force of E volts at frequency of f cycles per second is impressed, will be found from the relation

$$I = \frac{E}{2\pi f L} = \frac{E}{X_L}, \qquad (12)$$

which which L = the inductance of the coil in henrys; and
X_L = the reactance of the coil in ohms.

The necessary resistance of the coil always makes the current somewhat less than the value given by eq. 12.

Consider a coil of one henry connected to a 110-volt 60-cycle line. The reactance, X_L or $2\pi fL$, is found by calculation to be 377 ohms. Hence the current which flows must be equal to 110/377 = 0.292 ampere. In case the frequency is doubled, to 120 cycles per second, the reactance will be doubled to 754 ohms and the current will be halved to 0.146 ampere. Actually the current would be somewhat less than the values calculated above because of the resistance of the coil. The calculation which takes into account the resistance as well as the reactance will be given in a later section.

30. Condensers.—In radio circuits the condenser plays as important a part as does the coil, in fact the two are nearly always used together. A condenser is essentially two metal plates separated by a comparatively thin layer of insulating material, generally called the **dielectric** of the condenser.

Continuous current cannot flow through a condenser, because of the insulation between the plates; but alternating current, especially if the frequency is high, flows through it without difficulty. We say alternating current flows *through* a condenser but this does not mean that the insulation is punctured so that current actually jumps across from one plate to the other. Actually the condenser charges up in one direction, then discharges and charges in the opposite direction as the direction of the impressed alternating voltage changes. The current which is said to flow *through* a condenser therefore is really nothing but the charging current, alternating in direction with the same frequency as the impressed voltage.

According to the service they are to perform, condensers are made **variable** or **fixed.** For tuning radio frequency circuits variable condensers are used, generally consisting of two sets of rigid aluminum plates arranged to intermesh to any desired extent; air is nearly always used as the dielectric in such condensers. In Fig. 13 is shown a view of a variable condenser constructed so as to permit minute changes in its capacity; it is used for laboratory measurements.

Fixed condensers are generally used to permit an alternating current to flow through some circuit in which continuous current is to be prevented. They are frequently called "by-pass" condensers. The construction of such a condenser is shown in Fig. 14; this particular one is for use in telephone circuits. Two long sheets of aluminum foil are separated by thin sheets of waxed paper and the whole is rolled up into a compact form, impregnated and pressed to go into a small metal can container.

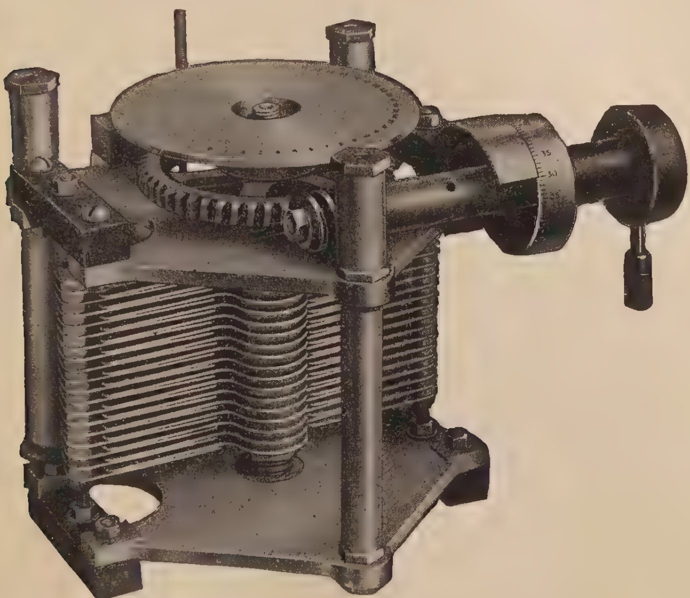

FIG. 13.—Variable condensers, using air or oil for dielectric, are extensively used in radio. There is shown here a high-grade variable air condenser for laboratory work; its maximum capacity is .0015 microfarad.

31. Capacity of a Condenser.—The capacity of a condenser gives an idea as to the amount of electricity required to charge it to a given voltage; the unit of capacity is the **farad.** A condenser having a farad of capacity would require one **coulomb** (one ampere flowing for one second) to charge it to one volt. No condenser has ever been built having a capacity of one farad; this unit is too large to be suitable for measuring the capacity of ordinary condensers. For fixed condensers the **microfarad,** abbreviated μf, is generally used as the unit; and for variable condensers the

micro-microfarad, abbreviated $\mu\mu f$, is a convenient unit. The first is one millionth of a farad and the second is one-millionth of a microfarad. The condenser shown in Fig. 13 has about 1500 micro-microfarads of capacity when the plates completely intermesh and about 40 micro-microfarads when the plates are completely disengaged. The condenser shown in Fig. 14 has two microfarads capacity—more than a thousand times greater than that of Fig. 13. The greater capacity is a result of the much greater area of plates, the small separation (the waxed paper is only 0.001 inch thick) and the use of wax for the dielectric.

32. Capacitive Reactance.—If a given condenser is connected to an alternating-current line it will be found that the charging cur-

FIG. 14.—The ordinary fixed condenser used in telephone and radio circuits is made up of very thin metallic sheets aluminum foil or tin foil) separated by wax-impregnated paper.

rent is directly proportional to the magnitude of the impressed voltage and directly proportional to the frequency of this voltage. Moreover, if a condenser of two microfarads is substituted for one of one microfarad it will be found that the charging current has doubled. Thus the current is proportional to the voltage, frequency, and capacity.

The quantity by which the voltage must be divided to give the current is called the reactance of the condenser and is generally designated by X_C. Careful measurement yields the relation that this capacitive reactance is equal to $\frac{1}{2\pi fC}$, that is, inversely proportional to both condenser capacity, and frequency.

33. Calculation of Capacity.—For certain simple forms the capacity of a condenser can be calculated. The formulas given below give the capacity in *centimeters;* to change to micro-microfarads the number of centimeters of capacity must be divided by 0.9.

For a sphere, completely isolated, as for example the earth

$$C = r \text{ cm.}, \quad \ldots \ldots \ldots \quad (13)$$

where r = the radius in centimeters.

For a pair of parallel flat plates, separated by air

$$C = \frac{A}{4\pi d} \text{ cm.}, \quad \ldots \ldots \ldots \quad (14)$$

where A = the area of one side of one plate in square centimeters;
d = the distance between plates in centimeters.

For a multiplate condenser such as used in tuning radio sets, the movable plates are one less in number than the stationary plates. The maximum capacity is given by the formula

$$C = \frac{2nA}{4\pi d} \text{ cm.}, \quad \ldots \ldots \ldots \quad (15)$$

where A = the area of one side of a movable plate in square centimeters;
n = the number of movable plates;
d = the distance separating a movable plate from a stationary plate, in centimeters.

For a by-pass condenser constructed as in Fig. 14

$$C = \frac{2kA}{4\pi d} \text{ cm.}, \quad \ldots \ldots \ldots \quad (16)$$

where A = area of one side of one sheet in square centimeters;
d = thickness of paper in centimeters;
k = specific inductive capacity of the waxed paper.

As illustrations of the use of these formulas we first note that the capacity of the earth, a sphere far distant from any other bodies, is about $4000 \times 5{,}280 \times 12 \times 2.54 = 640{,}000{,}000$ cm. To get micro-microfarads we divide by 0.9 and so get about 7.1×10^8 and this is equal to 710 microfarads.

As we know that the potential to which a condenser is charged is equal to Q/C where Q is the charge put upon it and C is the capacity, it follows that if one coulomb of electricity is put on the earth (say by clouds of electrons coming from the sun) the voltage of the earth would be changed about 1400 volts.

Consider a variable tuning condenser having 5 rotating plates and 6 fixed plates. The rotating plates are semicircular, each of 6 square inches area. The air space separating a rotating plate from its neighboring fixed one is 0.05 inch. What is the capacity when the plates are completely meshed? We change the dimensions to centimeters and use eq. 15. The capacity is calculated to be 244 cm. or 270 $\mu\mu f$.

The condenser shown in Fig. 14 has aluminum foil plates each 3 inches $\times$ 30 feet and the thickness of the paper is 0.001 inch. The paper, after being impregnated with wax, has a specific inductive capacity of 2.3. Changing dimensions to the metric system and using eq. 16, we find the capacity to be 1.12 μf.

34. Current Flow in a Condenser Circuit.—In a previous section we have mentioned the fact that an inductance cannot be built without resistance, but the same statement scarcely holds good for a condenser. This can be built with losses so small that for all ordinary calculations they may be neglected; this means that the only feature of the condenser which limits the flow of current is its reactance. Corresponding to eq. 12, then, we have for a condenser therefore current I in amperes

$$I = \frac{E}{X_C} = \frac{E}{\dfrac{1}{2\pi fC}} = 2\pi fCE, \quad . \quad . \quad . \quad . \quad . \quad (17)$$

C being in farads and E being in volts.

In the inductive circuit the current flow was *inversely* proportional to the frequency (see eq. 12) and in the condenser the current is *directly* proportional to the frequency, if the voltage remains constant.

As an illustration of the law we calculate the current flow into a 5 μf condenser connected to a 110-volt 60-cycle line. This is found (from eq. 17) to be

$$I = 2\pi 60 \times 5 \times 10^{-6} \times 110 = 0.208 \text{ ampere.}$$

An antenna has a capacity of $0.0016\mu f$ and is connected to a 200-volt 1,000,000-cycle source of power. The current which flows is equal to

$$2\pi \times 10^6 \times 0.0016 \times 10^{-6} \times 200 = 2.01 \text{ amperes.}$$

35. Current Flow in Coil having Resistance.—Actual coils do have resistance and generally this cannot be neglected, hence eq. 12 does not in general suffice for practical calculations. The flow of current in an actual coil is limited by its *impedance* and this depends upon both the resistance and the reactance of the coil. It is not the arithmetical sum of these two quantities but is the square root of the sum of their squares, as is shown in any text on alternating-current theory. The symbol for impedance is Z, and we have

$$Z = \sqrt{R^2 + X^2}. \qquad (18)$$

This equation holds good for a coil having resistance and also for a condenser having a resistance in series with it.

A coil of 10 ohms resistance and 0.1 henry inductance is connected to a 100-volt 60-cycle line. How much current flows?

The reactance, $2\pi fL$, is found to be 37.7 ohms, so the impedance is $\sqrt{10^2 + 37.7^2} = 38.9$ ohms. The current flow is therefore $110/38.9 = 2.83$ amperes. If the voltage is held fixed and the frequency is varied the current through the coil has values as shown in Fig. 15. At zero frequency the current is limited by resistance only and so is 10 amperes. At very high frequencies the resistance is negligible compared to the reactance and so current may be calculated from the reactance alone without appreciable error.

36. Phase of Current in Inductive Circuit.—If a sine wave of voltage is impressed on a coil a sine wave of current will flow, the magnitude of which can be calculated as above. The current, however, does not have the same phase as the voltage but lags behind. That is, the current does not have its maximum value when the voltage has its maximum value, but a fraction of a cycle later. The same remark holds good for the zero values or for any other two corresponding values. The angle between the voltage and current is called their **phase difference.**

If a coil had no resistance at all the current would lag behind the voltage by $\frac{1}{4}$ of a cycle, that is 90°. This is the theoretical limit of the phase difference and is never reached in actual coils. In the

coils used for the tuned radio frequency circuits of a good receiver the angle of lag may be as much as 89° but in ordinary power engineering circuits the angle of lag in an inductive circuit seldom exceeds 70°.

The angle of lag depends entirely upon the ratio of circuit

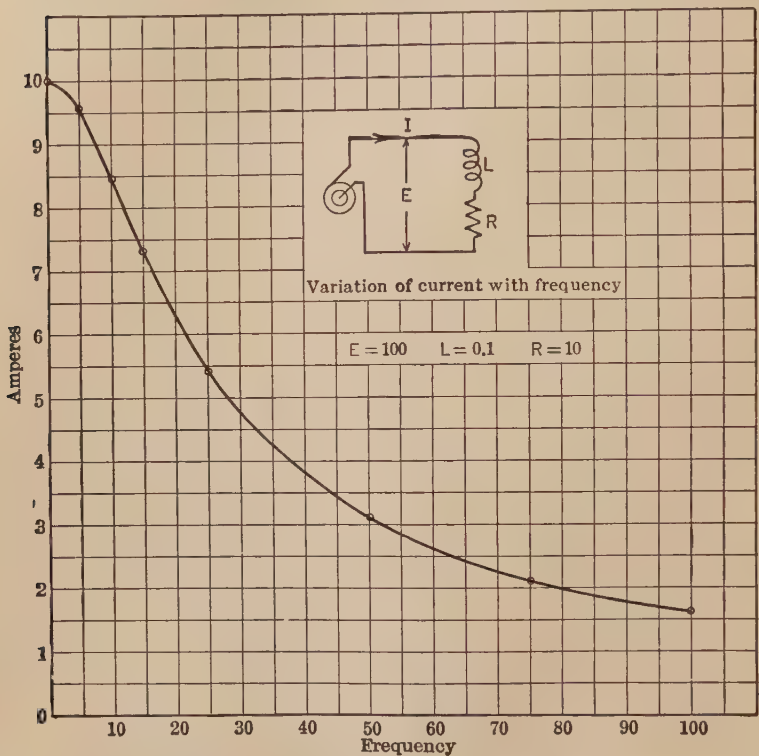

FIG. 15.—In an inductive circuit, the current which flows varies with frequency as shown here, voltage impressed being maintained constant.

reactance to circuit resistance. If these happen to be equal the angle of lag is 45°. If we call the angle of lag ϕ, as is customary, we have the relations

$$\cos \phi = \text{power factor of circuit} = \frac{R}{Z}. \quad . \quad . \quad . \qquad (19)$$

The angle may also be defined by the relation

$$\sin \phi = \frac{X}{Z} \quad \text{or} \quad \tan \phi = \frac{X}{R}.$$

If for example the reactance of an inductive circuit is 5 ohms and the resistance is 8.66 ohms we know from eq. 18 that the impedance, Z, is 10 ohms. Then $\cos \phi = 0.866$ and $\phi = 30°$.

In Fig. 16 are shown the possible phase relations in an alternating-current circuit. In (a) the circuit is resistive only and the current is in phase with the voltage; the phase difference is zero. In (b) the current lags behind the voltage (goes through its zero

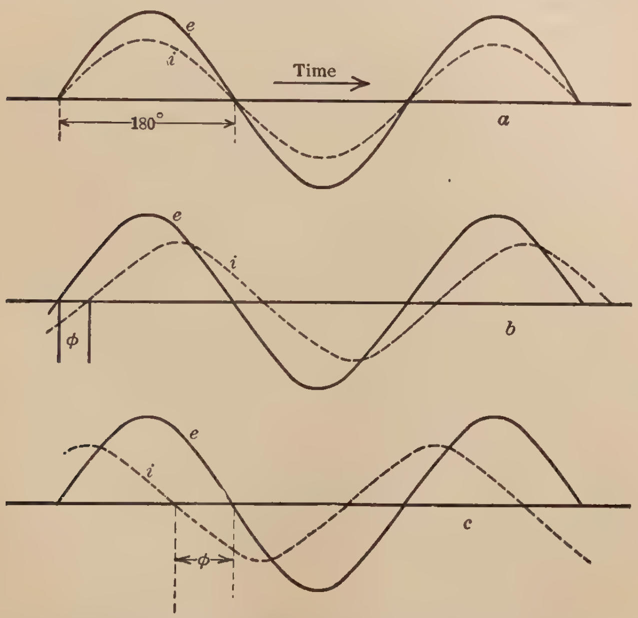

FIG. 16.—The current, in an alternating-current circuit, may flow in phase with the voltage impressed, as at a, may lag by some angle ϕ (between zero and 90°) as in b, or may lead by an angle ϕ (between zero and 90°) as in c.

value later than the voltage goes through its corresponding value) by about 30° and so represents the condition in the circuit calculated above.

37. Circuit having Condenser and Resistance in Series.—In such a circuit the current is calculated just as it was for a coil having a resistance in series. The reactance of the condenser is first calculated and then the impedance is calculated by Eq. 18. Let us suppose a condenser of 50 microfarads in series with 30 ohms resistance connected to a 110-volt 60-cycle line. The con-

denser reactance $\frac{1}{2\pi fC}$, is found to be 53.2 ohms and this in combination with the resistance of 30 ohms gives an impedance of 61 ohms. The current will therefore be $110/61 = 1.8$ amperes. The power factor $\cos \phi = \frac{30}{61} = 0.48$.

A condenser tends to make the current lead the voltage; in case there happens to be no resistance in series with the condenser the angle of lead is practically 90°. But in the example above the angle of lead is the angle whose cosine is 0.48 and this proves to be 59°. So in this circuit the current leads the voltage by 59° and this is the condition shown in curve *c* of Fig. 16.

38. Circuits having Resistance, Coils and Condensers.—From what has been previously said the current in such a circuit will depend upon each of the three factors, resistance, inductive reactance, and capacitive reactance. The magnitude of the current will depend upon the impedance and this must be calculated from the three factors mentioned. Just how to combine these to get the impedance depends upon how the coils and condensers are connected, whether in series, or parallel. Whether the current leads the voltage or lags behind it will depend upon whether the condenser effect predominates or the coil effect predominates. The question is discussed more in detail in the next chapter.

CHAPTER II

LAWS PARTICULARLY USEFUL IN RADIO CIRCUITS

1. Peculiar Behavior of Radio Circuits.—In the first chapter we reviewed the simple laws dealing with electric circuits in general. These general laws are of course applicable to radio circuits but in addition to these general laws there are some special laws and concepts having to do primarily with the circuit arrangements found principally in radio engineering; such will be taken up in this chapter. We shall find that when the frequency is high, measured perhaps in millions of cycles per second as it is in radio, effects which are of no importance for 60-cycle circuits may become the prime factors of the problem and such a simple idea as resistance becomes very complex and difficult to analyze completely. A piece of apparatus which we can see is a coil, may at high radio frequencies act like a condenser. With a coil and condenser connected in series to a source of radio frequency voltage it may be that the voltage across *either* the coil or condenser may be 100 times as great as that of the source. Such effects evidently follow laws not generally encountered in electric power engineering and it is these special laws which are taken up in this chapter.

2. Resistance in Radio Circuits.—The resistance of a coil can easily be measured in a continuous current circuit by ammeter and voltmeter readings. But if the coil is now put in a radio frequency circuit it will act as though its resistance were much greater and measurements will show this to be true. The resistance of a coil may be ten or even a hundred times as much as its continuous-current value when carrying high-frequency radio currents. This is due to several causes a few of which we take up.

3. Skin Effect.—In a continuous-current circuit the current flows uniformly through all parts of the cross-section of the wire; at radio frequencies comparatively little current flows through the center part of the wire, most of it concentrating in a comparatively thin layer at the surface of the wire. Of course if the current flows

through only the outer layer of the wire the copper in the center of the wire is useless and the wire acts as though its cross-section were only that of the outer layer or skin. This tendency for the high-frequency current to use only the outer part of the wire is called the **skin effect.** It increases rapidly at high frequency so

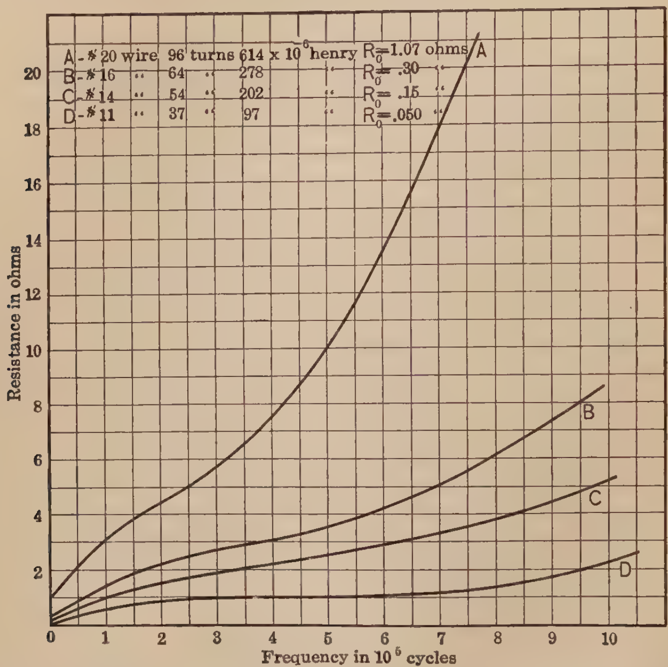

FIG. 17.—Resistance variation of solid-wire, single-layer solenoidal coils.

that the resistance of a coil for a million-cycle current may be many times that for low-frequency current. Fig. 17 shows some typical results for some single-layer coils 4 inches in diameter. The coil wound with No. 11 wire has a resistance at 10^6 cycles, 40 times as great as its value for continuous current and the coil of No. 16 wire has a resistance 26 times as great at 10^6 cycles as for continuous current. It can be seen from the curves that for higher radio frequencies (above 10^6 cycles) the resistance increases very fast.

4. Resistance Due to Iron Loss and Dielectric Loss.—A coil which employs an iron core for its magnetic circuit is not suitable at all for the higher radio frequencies, but may sometimes be used

for the lower radio frequencies. For audio-frequency circuits iron core coils are practically always used.

In such coils there is always some skin effect present, increasing the resistance of the coil but the measured value of resistance in an alternating-current circuit is much greater than can be accounted

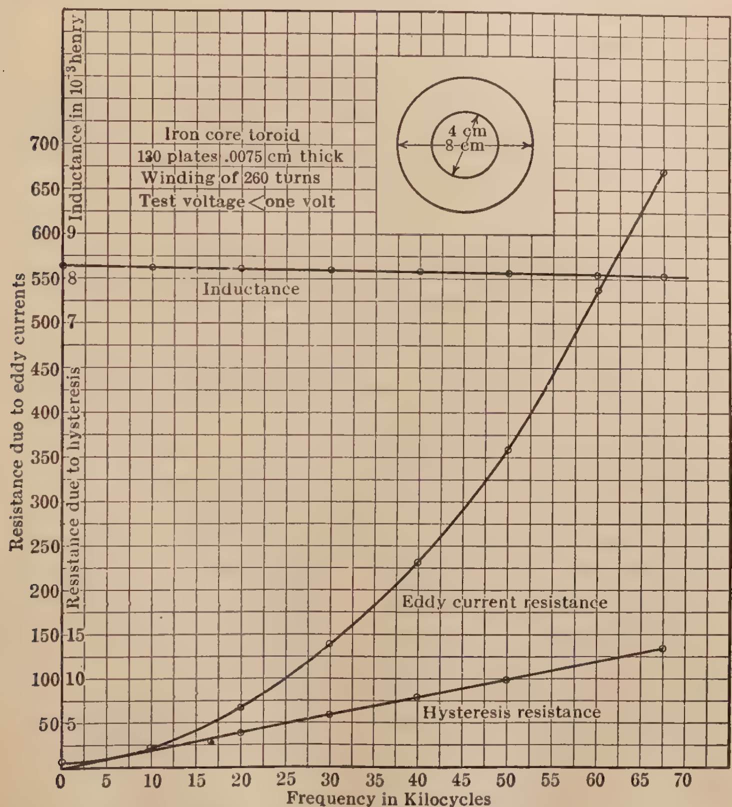

FIG. 18.—Effective resistance and inductance of an iron core coil. The wire resistance was negligible compared to that due to eddy-current and hysteresis losses. Eddy-current resistance varies nearly as the square of the frequency.

for by skin effect. The iron core has in it a continually reversing magnetic field and this produces power loss in the iron due to *hysteresis loss* and *eddy-current loss.* These power losses must be supplied by the current in the coil and their effect is to cause an increase in the effective resistance of the coil. In Fig. 18 are shown

the results of a test in an iron core coil. The actual resistance of the copper wire winding was only 5 ohms, but the measured resistance of the coil at 50 kilocycles was 368 ohms, 5 ohms due to the winding itself, 8 ohms due to hysteresis loss in the iron core, and 355 ohms due to eddy current loss in the iron core.

In a condenser there is always some loss of power in the dielectric; when measuring the capacity and resistance of a condenser in an alternating-current bridge or similar method the dielectric loss will appear as a part of the equivalent series resistance of the condenser. And, of course, the tin-foil plates themselves have an appreciable resistance. Even in the variable condensers used in radio receivers, having air for their dielectric, there is power loss in the insulating supports, etc., giving an equivalent series resistance which is generally about one-hundredth as much as the reactance of the condenser.

5. Resistance Caused by Radiation.—The antenna of a transmitting station is made up of two or three hundred feet of quite heavy copper wire; evidently its resistance cannot be more than one or two ohms yet when the resistance is measured at radio frequency by some convenient method, it is found to be perhaps 30 or 40 ohms. Furthermore this resistance increases very rapidly as the frequency of current is increased.

The antenna of a transmitting station is designed to radiate, or throw off, electric energy into space; the power so lost will cause the measured value of antenna resistance to increase by a corresponding amount. This increase in resistance is called the *radiation resistance* of the antenna. It is the object of the radio engineer to make this resistance as large as possible because it is a measure of the power radiated into space and this is what the antenna is designed to do.

6. Current Flow in a Circuit having Resistance, Inductance and Capacity in Series.—This is by all means the most important circuit used in radio apparatus. If an alternating-current generator is connected to the circuit, as shown in Fig. 19, how much current will flow?

In Fig. 19 the resistance R is shown separate from the coil L, which is indicated as having no resistance. In the actual radio circuit the resistance is actually the resistance of the coil and the series resistance of the condenser is generally negligible compared to that of the coil. If it has an appreciable resistance the circuit

resistance, R of Fig. 19, must be taken as the sum of the coil resistance and that of the condenser. There are three factors which tend to limit the current in the circuit, resistance, inductive reactance, and capacitive reactance, or we may say there are three voltages for the alternator to supply, the RI voltage, the IX_L voltage, and the IX_C voltage.

Treating the problem from the standpoint of resistance, react-

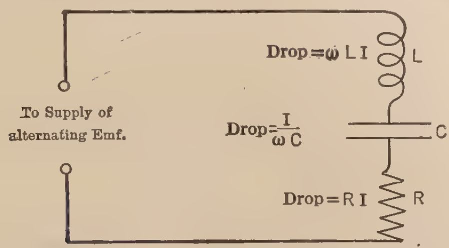

FIG. 19.—A series circuit containing resistance, inductance and capacity.

ance and impedance we note that as the effect of the inductive reactance is to make the current lag and the effect of the capacitive reactance is to make the current lead, these two reactances acting in the circuit at the same time *must tend to neutralize one another.* That is the total reactance of this series circuit is the difference of the two reactances, instead of their sum. Calling X the total circuit reactance we have

$$X = X_L - X_C. \qquad (20)$$

As in the simpler circuits treated in Chapter I, we have

$$Z = \sqrt{R^2 + X^2},$$

and this now becomes

$$Z = \sqrt{R^2 + (X_L - X_C)^2}. \qquad (21)$$

Writing for X_L and X_C their proper values (see p. 28 and p. 34) we get

$$Z = \sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2}, \qquad (22)$$

so that

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2}}. \qquad (23)$$

This equation must be carefully analyzed, as it is the basis of tuning and selectivity in radio receivers.

Let us suppose a coil of 0.15 henry inductance and 14 ohms resistance in series with a condenser of 30 microfarads capacity and negligible series resistance. The two are connected in series to a 110-volt 60-cycle alternator. How much current flows? What is the power factor of the coil and what is the power factor of the circuit? What is the voltage across the coil and what is the voltage across the condenser?

The coil reactance $X_L = 2\pi fL = 56.5$ ohms

Condenser reactance $X_C = \dfrac{1}{2\pi fC} = 88.5$ ohms

Circuit reactance is equal to $(56.5 - 88.5) = -32$ ohms.

(The minus sign indicates merely that the capacity effect predominates over that of the coil.)

The impedance is $\sqrt{14^2 + (-32)^2} = 34.8$ ohms.

Current $= \dfrac{110}{34.8} = 3.15$ amperes

Impedance of the coil $= \sqrt{14^2 + 56.5^2} = 58.5$ ohms.

Power factor of coil $= \dfrac{14}{58.5} = 0.24.$

Power factor of circuit $= \dfrac{14}{34.8} = 0.401$

Voltage across coil $= IZ_L = 3.15 \times 58.5 = 184$ volts.

Voltage across condenser $= IX_C = 3.15 \times 88.5 = 278$ volts.

A remarkable thing is at once noticed. *The drop across the coil is greater than the voltage impressed on the circuit by the alternator, as is that across the condenser.*

We will now consider a radio circuit, consisting of a coil of 250 microhenrys and 20 ohms resistance in series with a condenser of 110 micro-microfarads. If the voltage induced in the circuit is 4 millivolts at a frequency of 1000 kilocycles, what is the current, and what is the voltage across the condenser and the coil?

The coil reactance is $2\pi \times 10^6 \times 250 \times 10^{-6} = 1570$ ohms

Capacity reactance is $\dfrac{1}{2\pi \times 10^6 \times 110 \times 10^{-12}} = 1450$ ohms.

Total reactance is $1570 - 1450 = 120$ ohms.

Impedance $= \sqrt{20^2 + 120^2} = 122$ ohms.

Current $= \dfrac{0.004}{122} = 32.8$ micro-amperes.

Drop across condenser $= 32.8 \times 10^{-6} \times 1450 = 0.0476$ volt.

Drop across coil $= 32.8 \times 10^{-6} \times 1570 = 0.0515$ volt.

In this problem also it will be noticed that the drop across either the coil or condenser is much greater than the voltage which is setting up the current, that is, in this case, the voltage induced in the circuit. Whereas this is 4 millivolts, the drop across the coil is 51.5 millivolts or nearly thirteen times as great.

7. Resonance and Resonant Frequency.—If we imagine that the circuit studied in the previous section has impressed upon it a voltage of fixed magnitude and varying frequency some interesting effects are disclosed. The two reactances, $2\pi fL$ and $\dfrac{1}{2\pi fC}$ vary with frequency in the manner shown in Fig. 20. The inductive reactance $2\pi fL$ increases directly in proportion to the frequency and the capacity reactance $\dfrac{1}{2\pi fC}$ varies inversely as the frequency. Such being the fact it is evident that, no matter what the respective values of L and C may be, *some value of frequency must give the same numerical value for the two reactances.* But as the total reactance of the circuit is the arithmetical difference of these two reactances it follows that such frequency as results in the same value for the two reactances gives zero value for total reactance of the circuit. Such frequency is called the *resonant frequency of the circuit.*

For such resonant frequency Eq. 23 reduces to

$$I = E/R, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

and the power factor of the circuit is unity.

To find the resonant frequency of any series circuit of this nature we equate the two reactances and get

$$2\pi fL = \frac{1}{2\pi fC},$$

or

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \quad \ldots \ldots \quad (25)$$

in which f_r is the resonant frequency of the circuit, and L and C are measured in henrys and farads respectively.

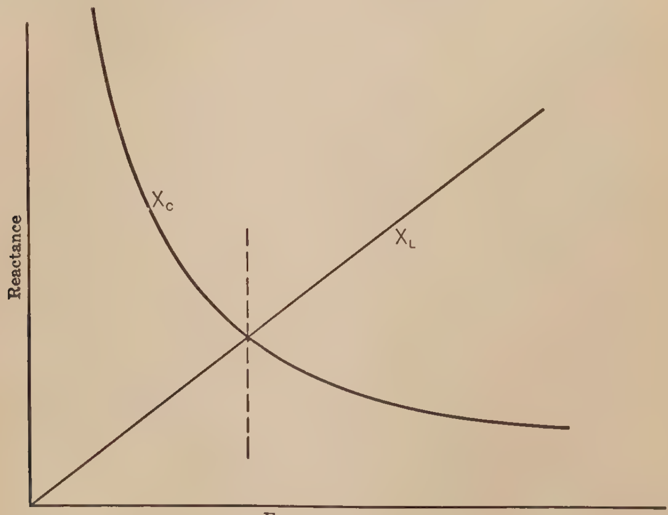

FIG. 20.—Showing how inductive reactance and capacitive reactance vary with frequency.

As mentioned before ordinary condensers used in engineering work, are measured in microfarads and then eq. 25 may be changed to the convenient form

$$f_r = \frac{1{,}000}{2\pi\sqrt{LC_{\mu f}}}. \quad \ldots \ldots \quad (26)$$

In the case of radio circuits where L and C are both given in micro-units, we write for convenience

$$f_r = \frac{10^6}{2\pi\sqrt{L_{\mu h}C_{\mu f}}}. \quad \ldots \ldots \quad (27)$$

At resonant frequency unexpectedly large values of current flow and the drop across either coil or condenser, compared to the voltage impressed on the circuit, is equally unexpectedly large.

Consider a coil of 0.2 henry and 4 ohms resistance in series with $30\mu f$ of capacity, what is the resonant frequency? If at this frequency 20 volts are impressed on the circuit how much current flows and what is the drop across both coil and condenser? What is the power factor of the coil and of the circuit at resonant frequency?

$$f_r = \frac{1000}{2\pi\sqrt{0.2 \times 30}} = 65 \text{ cycles}$$

$$I = \tfrac{20}{4} = 5 \text{ amperes}$$

Coil reactance at 65 cycles = 80.6 ohms
Condenser reactance at 65 cycles = 80.6 ohms
Drop across condenser = 403 volts
Impedance of coil = $\sqrt{4^2 + 80.6^2} = 80.8$ ohms
Drop across coil = 404 volts
Power factor of coil = 4/80.8 = 0.0495
Power factor of circuit $= \dfrac{R}{Z} = \dfrac{R}{R} = \dfrac{4}{4} = 1.00$

An antenna having 0.0024 μf capacity has in series with itself an inductance of 125 micro-henrys. For what frequency is the circuit resonant?

Using eq. 27 we find

$$f_r = \frac{10^6}{2\pi\sqrt{0.0024 \times 125}} = \frac{10^6}{2\pi \times 0.55} = 286{,}000 \text{ cycles} = 286 \text{ kilocycles}$$

In a radio receiver the tuned circuit has a coil of 180 micro-henrys. At what value must the variable condenser (in series with the coil) be set to tune the circuit for a frequency of 610 kc.?

Transposing eq. 27 we get

$$\sqrt{LC} = \frac{10^6}{2\pi f_r} \quad \text{or} \quad LC = \frac{10^{12}}{(2\pi f_r)^2} \quad \text{or} \quad C = \frac{10^{12}}{(2\pi f_r)^2 \times L}$$

Using this relation we solve our problem

$$C = \frac{10^{12}}{(2\pi \times 610{,}000)^2 \times 180} = 0.000377\mu f$$

8. Wave Meter and How Used.—In the early days of radio the frequency of the radio current was seldom mentioned; the **wave length** of the circuit was used instead of frequency. Because of this usage an instrument for measuring the frequency of a radio current was called a **wave meter.** This name still persists although a more suitable name for the instrument would be a **frequency meter.**

A wave meter is nothing more than a carefully constructed and accurately calibrated circuit consisting of a fixed coil in series with a variable condenser. Generally an indicating instrument of some kind is built into the circuit for showing with what adjustment of the variable condenser a maximum current is flowing in the circuit. Fig. 21 shows the arrangement practically always used. A hot-wire ammeter serves to show the current in the circuit. The moving plates of the condenser carry a rigid pointer which, moving over a carefully calibrated scale, serves as a wave length or frequency indicator.

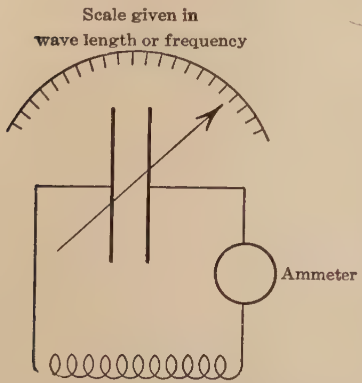

FIG. 21.—A wave meter, or frequency meter, is merely a series resonant circuit, resonance being established by changing the setting of the variable condenser. A sensitive hot wire, or thermo-couple, ammeter generally serves to indicate resonance.

Frequently the meter is so constructed that one of several coils may be used. By making the inductance of one coil about six times as great as the next smaller one in the set, the meter serves for covering a large wave length, or frequency, range.

With one coil the frequency range covered by the variable condenser is about three to one, that is, with minimum readable value of the variable condenser the resonant frequency of the circuit is three times as great as the resonant frequency when all of the variable condenser is used. Thus to cover a frequency range from 500 kc. to 1500 kc. one coil will suffice but to cover a range from 100 kc. to 10,000 kc. we would have to use five different coils.

In use the wave-meter coil is brought near a coil or wire in which the current of unknown frequency is flowing, so that an induced

voltage (due to mutual induction) is set up in the wave-meter circuit. As previously shown, when the resonant frequency of the circuit is the same as that of the impressed voltage a maximum current is set up in the circuit. Thus the variable condenser of the wave meter is slowly changed until the wave meter ammeter reads a maximum current. Under this condition we know that the reactance of the wave-meter circuit is zero (eq. 24) and that the

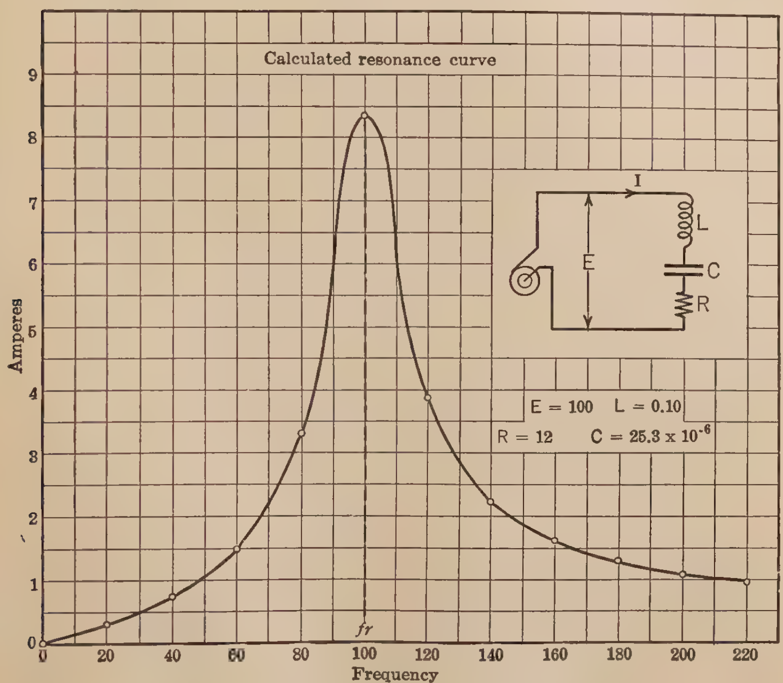

FIG. 22.—A calculated resonance curve.

impressed voltage has a frequency the same as the resonant frequency of the circuit. Hence by reading from the wave-meter scale the resonant frequency for this setting of its condenser we know accurately the frequency of current in the circuit being measured.

9. Selectivity in a Radio Circuit.—The modern broadcast receiver must have the quality known as **selectivity**; that is, if several different stations are broadcasting at the same time, the receiver must have the ability to " bring in " the desired station

and eliminate the others. This is possible because the different stations send out signals of different frequencies. After the signal has been received by the antenna it is generally passed along through the amplifier through **tuned circuits,** that is, circuits consisting of coils in series with condensers. It is the action of these tuned circuits which gives the set its selectivity.

In Fig. 22 is shown the performance of a tuned circuit, for vari-

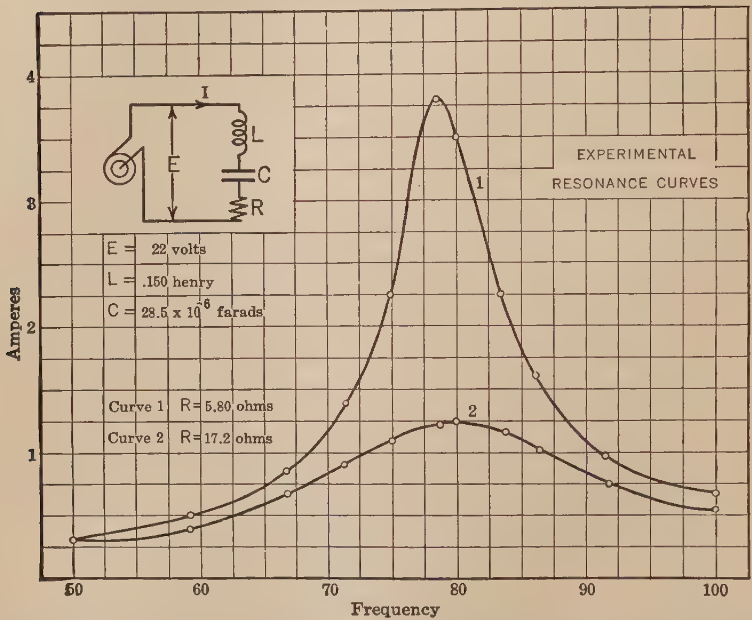

FIG. 23.—Experimental resonance curves; the resonance frequency is actually independent of circuit resistance. A slight experimental error brings these two resonance peaks about one cycle apart.

ous frequencies. The voltage impressed on the circuit was assumed the same for all frequencies but it will be seen that the amount of current set up in the circuit varied greatly as the frequency was changed. Thus at 60 cycles the current is only 1.5 amperes while at 100 cycles the current is over 8 amperes. It may be calculated that 100 cycles is the resonant frequency for the inductance and capacity used. It is evident that this circuit would act selectively for the 100-cycle current.

In Fig. 23 are shown experimental curves to bring out the effect of circuit resistance upon its selectivity. With 5.8 ohms resistance

the circuit is quite selective for 79 cycles. After the circuit resistance has been increased to 17.2 ohms it is still resonant at the same frequency but the resonant quality is by no means as prominent. With the lower value of resistance the current at resonance is 5.5 times as great as the current at 100 cycles; with the higher resistance the current at resonance is only twice as much as the 100-cycle current. Thus we reach the conclusion: the selectivity of a circuit decreases as its resistance is increased, other factors remaining the same.

As will be shown in the next section the selectivity depends really upon the ratio of the coil resistance to the coil reactance; the lower this ratio the greater is the selectivity.

10. Decrement and how Determined.—A quantitative idea of the selectivity of a circuit is obtained if its *decrement* is known;

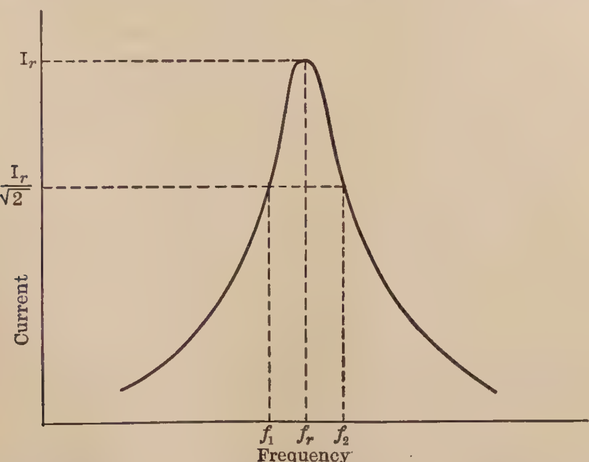

FIG. 24.—Indicating the two "half energy" points in the resonance curve. At these two frequencies the power delivered to the circuit is one-half that delivered at the resonance frequency.

the lower the decrement the sharper is the resonance or the greater is the selectivity. In Fig. 24 we have shown a resonance curve upon which three frequencies are shown, f_r, f_1 and f_2. That marked f_r is the resonant frequency of the circuit, for which the current is I_r. The two other frequencies are those for which the current is $\frac{1}{\sqrt{2}}$ of the resonance value. Evidently the sharper the

resonance the closer will f_1 and f_2 approach f_r, so a measure of the circuit's selectivity may be taken as $\frac{f_2 - f_1}{f_r}$. It can be shown that $\frac{f_2 - f_1}{f_r} = \frac{R}{2\pi f_r L}$ and this may be written

$$\frac{R}{2f_rL} = \pi\frac{f_2 - f_1}{f_r}. \quad \text{(28)}$$

Now the quantity $\frac{R}{2f_rL}$ has a peculiar significance from an entirely different viewpoint; it is this quantity which determines how rapidly oscillatory currents, which may have been set up in the circuit, die away. It is called the **decrement** of the circuit and generally denoted by the Greek letter δ.

So we have

$$\delta = \frac{R}{2f_rL}. \quad \text{(29)}$$

We may say then that the selectivity of the circuit is inversely proportional to the decrement. Or if we call $\frac{f_r}{f_2 - f_1}$ the selectivity factor we see that

$$\frac{f_r}{f_2 - f_1} = \frac{2\pi f_r L}{R} = \frac{X_L}{R}. \quad \text{(30)}$$

Thus a measure of the selectivity of a circuit is the ratio of the coil reactance, at resonant frequency, to the resistance.

Furthermore when R is small compared to X_L, which is the case for all good radio coils, we see that Z, the impedance of the coil, and X_L are practically the same thing, so that for $\frac{R}{X_L}$ we may put $\frac{R}{Z}$.

From this relation and Eq. 29, we then get

$$\delta = \pi\frac{R}{2\pi f_r L} = \pi\frac{R}{X_L} = \pi\frac{R}{Z} = \pi \cos\phi_L. \quad \text{(31)}$$

This says that the decrement of a circuit is equal to π multiplied by the power factor of the coil. Here, as in previous demonstra-

tions, the series resistance of the condenser has been considered negligible compared to the coil resistance; this is generally permissible.

The antenna circuit of the ordinary ship's radio has a decrement of 0.10 to 0.15. A low resistance circuit set up in the laboratory for testing purposes may have a decrement of about 0.03. It is possible to build circuits which show a decrement as low as 0.01, but this is exceptional. A good wave meter has a decrement of about 0.02.

11. Law for Parallel Circuits.—We shall not discuss here the general law for current flow in parallel circuits, but only that case of particular interest in radio. Suppose a coil is shunted by a condenser, how much current does the line have to supply, and what is the phase of this current with respect to the line voltage? Does the circuit act like a coil or a condenser and of what inductance or capacity?

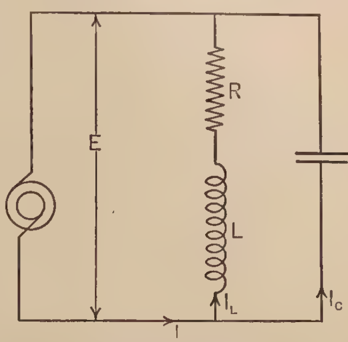

FIG. 25.—An inductance and condenser connected to show parallel resonance; at the resonant frequency the line current falls to a very small value.

The first point to emphasize in this problem (Fig. 25) is that the current taken by each branch of the circuit is exactly the same as though the other branch were not present. So each branch of the circuit is figured as a simple circuit. That is

$$I_L = \frac{E}{\sqrt{R^2 + X_L{}^2}},$$

and

$$I_C = 2\pi fCE.$$

The current I_L will lag behind the voltage by an angle given by the relation $\cos \phi = \frac{R}{Z}$ and the condenser current leads the voltage by practically 90°. The inductive current may be separated into two components

$$I_L \text{ active} = I'_L = I_L \cos \phi;$$

$$I_L \text{ reactive} = I''_L = I_L \sin \phi.$$

The reactive current I''_L lags behind the line voltage by 90° and the condensive current I_C leads the line voltage by 90°. Hence the reactive current furnished by the line must be equal to $I''_L - I_C$. The active current taken by the inductance I'_L has no counterpart in the condenser branch hence the active current furnished by the line must be I'_L.

Therefore the total line current is given by

$$I_{\text{line}} = \sqrt{(I'_L)^2 + (I''_L - I_C)^2}, \quad \ldots \quad (32)$$

$$= \sqrt{I^2 + I'^2}. \quad \ldots \quad (33)$$

Whether the combination circuit acts like a condenser or coil depends entirely upon the relative values of I''_L and I_C. If I_C predominates the reactive current furnished by the line is a leading current and the combination acts like a condenser, in series with a certain value of resistance. If I''_L is greater than I_C then the combination acts like a coil, having, however, different inductance and resistance than the actual coil.

The equivalent coil or condenser is calculated as follows: Suppose I''_L (of eq. 32) predominates then I' (of eq. 33) is a current lagging 90° behind the line voltage. The impedance of the combination Z is given by

$$Z = E/I_{\text{line}}. \quad \ldots \quad (34)$$

The resistive component of this Z is given (in terms of the currents of eq. 33) by

$$R = Z \cos \phi_{\text{line}} = Z\frac{I}{I_{\text{line}}}, \quad \ldots \quad (35)$$

and the inductive reactance is given by

$$X = Z \sin \phi_{\text{line}} = Z\frac{I'}{I_{\text{line}}} \quad \ldots \quad (36)$$

Let us suppose a coil of $L = 0.150$ henry and $R_L = 5.8$ in parallel with a condenser of $28.5\mu f$ connected to a line of 110 volts at 70 cycles. How much current flows in the line and what is the electrically equivalent single circuit?

The impedance of the coil is

$$Z_L = \sqrt{5.8^2 + (2\pi 70 \times 0.15)^2} = 66.3 \text{ ohms}.$$

The current through the coil is $110/66.3 = 1.66$ amperes
Power factor ($\cos\phi$) of coil $= 5.8/66.3 = .0875$
Active current in coil $= 1.66 \times .0875 = 0.145$ ampere
Reactive current in coil $= \sqrt{1.66^2 - 0.145^2} = 1.65$ amperes
Condenser current $= 2\pi fCE = 2\pi 70 \times 28.5 \times 10^{-6} \times 110 = 1.38$ amperes
Active current supplied by line $= 0.145$ ampere
Reactive current supplied by line $= 1.65 - 1.38 = 0.27$ ampere
Line current $= \sqrt{0.145^2 + 0.27^2} = 0.307$ ampere
Power factor of line $= 0.145/0.307 = 0.472$
Impedance of line $= 110/0.307 = 358$ ohms
Resistance of line $= Z_{\text{line}} \cos \phi_{\text{line}} = 358 \times 0.472 = 169$ ohms
Reactance of line $= \sqrt{358^2 - 169^2} = 315$ ohms

As the reactive current in the coil branch is greater than that in the condenser branch the reactive current in the line is a lagging current, so the line reactance is an inductive reactance. So we write

$$2\pi fL' = 315 \quad \text{or} \quad L' = 0.72 \text{ henry.}$$

This means that the parallel circuit, coil of $L = 0.15$ henry and $R = 5.8$ ohms, shunted by the condenser of $28.5\mu f$ acts like a simple circuit consisting of a coil of 0.72 henry and 169 ohms resistance.

Now suppose the frequency of the line is increased to 90 cycles; what will the parallel circuit be equivalent to?

Coil impedance $= \sqrt{5.8^2 + (2\pi 90 \times 0.15)^2} = 85$ ohms
Coil current $= 110/85 = 1.29$ amperes
Active coil current $= 1.29 \times 5.8/85 = 0.0885$ ampere
Reactive current $= \sqrt{1.29^2 - 0.0885^2} = 1.28$ amperes
Condenser current $= 2\pi \times 90 \times 28.5 \times 10^{-6} \times 110 = 1.77$ amperes
Active current in line $= 0.0885$ ampere
Reactive current in line $= 1.77 - 1.28 = 0.49$ ampere

As the condenser current is larger than the reactive current of the coil the line reactive current is a leading one, and the line reactance will now be capacitive, instead of inductive as it was for the previous solution.

Line current $= \sqrt{0.0885^2 + 0.49^2} = 0.492$ ampere
Line impedance $= 110/0.492 = 224$ ohms
Line resistance $= 224 \times \dfrac{0.0885}{0.492} = 40.4$ ohm
Line reactance $= \sqrt{224^2 - 40.4^2} = 221$ ohms

Equivalent capacity is obtained by putting this reactance equal to $\frac{1}{2\pi fC'}$. From this we get $C' = 8.02\mu f$.

Therefore at 90 cycles this parallel circuit acts like a simple circuit of 40.4 ohms in series with a condenser of $8.02\mu f$.

In Fig. 26 we have shown these two solutions diagrammatically.

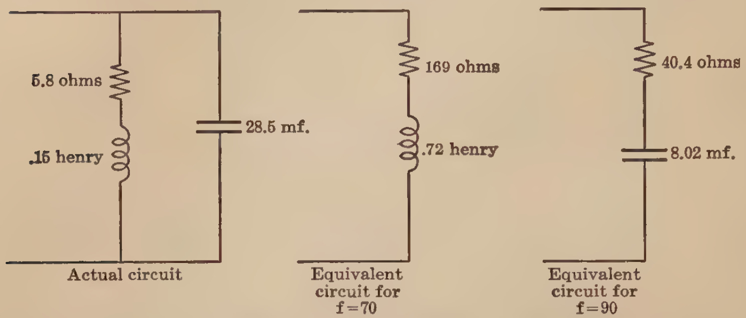

FIG. 26.—A coil and condenser in parallel connection act towards the line as either a coil or condenser, depending upon whether the impressed frequency is lower or higher than the resonance frequency; the equivalent circuit is here shown for one frequency below, and another above, resonance.

12. Resonance in Parallel Circuits.—A parallel circuit is said to be resonant when the line current is in phase with the line voltage; this is the same condition as defines resonance for a series circuit. To find the resonant frequency, therefore, we put the coil reactive current equal to the condenser current, and solve for the frequency.

Coil reactive current

$$= \frac{E}{\sqrt{R^2 + X_L{}^2}} \times \frac{X_L}{\sqrt{R^2 + X_L{}^2}} = \frac{2\pi fLE}{R^2 + \overline{2\pi fL}^2}$$

Condenser current

$$= 2\pi fCE.$$

Placing these two currents equal to each other and solving for f we get

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}. \quad \ldots \ldots \quad (37)$$

In most radio circuits this is not sensibly different from $f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$ and this, it will be recalled, is the formula for the resonant frequency of the series circuit. Hence we conclude that a given coil and condenser will show resonance for the parallel connection at essentially the same frequency as gives resonance when they are in series.

When the resonant frequency is impressed on the parallel circuit the line current is the same as the active current in the coil, the two reactive currents just neutralizing one another. The line impedance must be resistance only, but it will be found that this resistance is unexpectedly high. We have

$$R' = \frac{E}{\text{Active } I_{\text{coil}}} = E \bigg/ \frac{ER_{\text{coil}}}{R^2_{\text{coil}} + X_L^2} = \frac{R^2_{\text{coil}} + X_L^2}{R_{\text{coil}}},$$

and when R^2_{coil} is negligible compared to X_L^2 this reduces to

$$R' = \frac{L}{CR_{\text{coil}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37A)$$

For the problem previously discussed therefore, at resonant frequency (about 78 cycles)

$$R' = \frac{0.15}{28.5 \times 10^{-6} \times 5.8} = 910 \text{ ohms}$$

13. Adjustable Resistance of Parallel Resonant Circuit.—Fig. 27 shows a coil and condenser in parallel connection, the power supply being connected at points A and B. It is supposed that the frequency of the power supply has been adjusted to result in unity line power factor, that is, the coil and condenser in parallel act as though they were a circuit of resistance only. The value of this line resistance is equal to $\frac{L}{C}\frac{1}{R}$, where R is the actual resistance of the coil and condenser in series.

The value of this line resistance is very high, as shown in the illustration of the previous section. Let us consider that the coil of Fig. 27 has 250 microhenrys inductance and 15 ohms resistance and that the condenser C has been set at a value to establish resonance for the impressed frequency of 1000 kc. The condenser will have to be set at a value of $102\mu\mu f$.

The apparent impedance across points A–B will be resistance only, as previously shown. Its value will be equal to $\frac{L}{C}\frac{1}{R}$, or $\frac{250 \times 10^{-6}}{102 \times 10^{-12}} \times \frac{1}{15} = 164{,}000$ ohms. Now this value of resistance may be too high to serve the purpose at hand; it is therefore convenient that it is possible to connect the power supply at other points of the circuit and get a lower resistance.

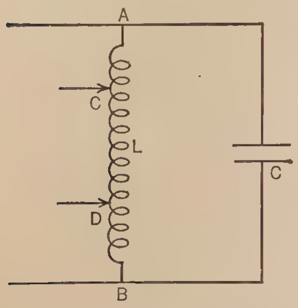

FIG. 27.—If resonant frequency is impressed on any two points of the circuit, this appears to the line as resistance only The magnitude of this resistance decreases as the points of power connection approach one another.

If the power supply, instead of being connected to points A–B is connected to points A–D, A–C or D–C, the circuit will still show parallel resonance, having resistance only, but this resistance will diminish in value as the two points of connection are moved closer together. Thus if the power supply is connected to points A–B the circuit shows 164,000 ohms resistance, if connected to points A–D it might show 100,000 ohms and if connected to points A–C it might show 10,000 ohms.

Thus by connecting one of the power lines to point A (or point B) and having the other connection to a variable contact moving along the coil, this parallel resonant circuit acts like a high resistance of adjustable value. This scheme is used a great deal in vacuum tube circuits, where it is necessary to match the resistance of the circuit to the resistance of the tube.

14. Coils Used in Radio and Reasonable Resistances.—The coils used in radio transmitters are entirely different from those used in receiving sets because of the much larger currents carried by the transmitter coils. Because of the very small number of transmitting sets built it is not reasonable to discuss their characteristics in a text like this, so the following remarks will deal only with the coils used in radio receivers.

In general a coil intended for use in a radio receiver should have as low a resistance as possible. The lower the resistance of the

coils used in its radio frequency circuits the greater is the selectivity of the set and, to some extent, the greater is its amplification.

In addition to having a low resistance the coil should have approximately the right inductance for the frequency range to be covered. For example, in tuning a circuit for 1000 kc. we might use a coil having $250\mu h$ and a condenser having $102\mu\mu f$. Or we might use a coil of $500\mu h$ and $51\mu\mu f$, or possibly a coil of $1000\mu h$ and $26\mu\mu f$. Going the other way we might use a coil of $125\mu h$ and $204\mu\mu f$ or one of $62\mu h$ and a condenser of $410\mu\mu f$.

All of these combinations will satisfy the requirements of giving resonance at 1000 kc. But it will be found that using coils of ordinary construction the choice of a "best coil" lies within quite narrow limits.

In attempting to use a coil with $1000\mu h$ inductance it will be found that the range over which the receiving set can be tuned is quite narrow. Ordinarily a well-designed set will give a useful frequency range of about 3 to 1 but it would be found that the set with $1000\mu h$ coils would give a range of probably less than 2 to 1. There is always a considerable amount of stray capacity in a receiving set in addition to the intentional capacity of the tuning condenser. The wiring of the set gives an appreciable capacity; the vacuum tubes themselves and their sockets as well as the coil, give stray capacities which interfere with tuning. In the average set this amount of capacity is about $30\mu\mu f$. The ordinary variable condenser has a minimum capacity of about $10\mu\mu f$, so that even when the tuning condenser is set at zero (minimum capacity) there is $40\mu\mu f$ of capacity connected to the coil.

If the set is to tune to as low as 500 kc. the maximum capacity for the $1000\mu h$ coil circuit would be $100\mu\mu f$. When the condenser is set at its minimum value there is $40\mu\mu f$ of capacity connected to the coil so that the resonant frequency is 950 kc. Thus the range of the set is less than 2 to 1.

If the coil of $62\mu h$ is used the variable condenser must have (to be resonant at 500 kc.) a capacity of $1600\mu\mu f$. The range of the set would now be from 500 kc. to 3160 kc., a very wide range. But such a condenser is much larger (and therefore more expensive) than necessary and furthermore it would be found that the selectivity of this set would be very poor.

It is evident, then, that the proper value of inductance for the desired frequency range (500 to 1500 kc.) must lie between $62\mu h$

and $1000\mu h$. Taking into consideration cost of coil and condenser, selectivity obtainable, frequency range obtainable, etc., it will be found that a coil of about $250\mu h$ is most suitable. Such a coil will require only a reasonably large variable condenser, of maximum capacity $400\mu\mu f$. The range of the set will be 500 kc. to 1580 kc. and the selectivity will be satisfactory if the coil is well constructed.

As a result of "cut and try" it will be found that for frequencies in the broadcast band a coil should have a reactance of about 1500 ohms, for the highest frequency at which it is to be used. This is not a very definite value as it depends to some extent upon how the coil is built. It may be as low as 1000 ohms or as high as 2000 ohms but for a well-built coil the 1500-ohm value is generally the best.

The reactance of a good radio coil should be from 100 to 200 times as much as its resistance. This is the same as saying that its power factor should be as low as $\frac{1}{2}$ to 1 per cent. The resistance of a given coil goes up with increasing frequency due to the greater losses at the higher frequencies, so that the ratio of reactance to resistance will be nearly the same for all the frequencies for which the radio set is designed.

In Fig. 28 are shown curves for the resistance of a few coils made with different kinds of wire. One set of coils (subscript 1) had $369\mu h$ inductance and the other set (subscript 2) had $195\mu h$ inductance. It can be seen that for all six coils the resistance increases almost proportionately with the frequency in the lower frequency range. With higher frequencies the resistance increases much faster than the frequency; here the coil is unsuitable for a radio receiver as its use will result in poor selectivity.

From the curves of Fig. 28 the power factors of the coils can be calculated; it will be found that for all six coils throughout the frequency range shown the power factor is about $\frac{1}{2}$ per cent.

15. Use of Stranded Wire for Coils.—As previously shown, it is generally advantageous to have the resistance of coils used in radio circuits as low as feasible. The skin effect makes the current leave the center part of a wire as radio frequencies, resulting in a resistance increasing rapidly at the higher frequencies in the broadcast range. To prevent this coils are frequently wound with a specially constructed cable, sometimes called by the German name *litzendraht*.

These cables are made of many strands of fine wire, each of the

fine wires being itself an enamel insulated wire. By properly weaving these fine wires together into a cable the skin effect is very much reduced for frequencies as high as about 1000 kc. The effect on resistance of such a cable, as compared to solid wire, is well shown in Fig. 28. The two coils designated as A_1 and A_2 were of No. 20 solid wire; the two designated as B_1 and B_2 were made with a braided cable consisting of 32 No. 36 enameled wires and those designated as C_1 and C_2 were of a specially twisted cable consisting of 48 No. 38 enameled wires.

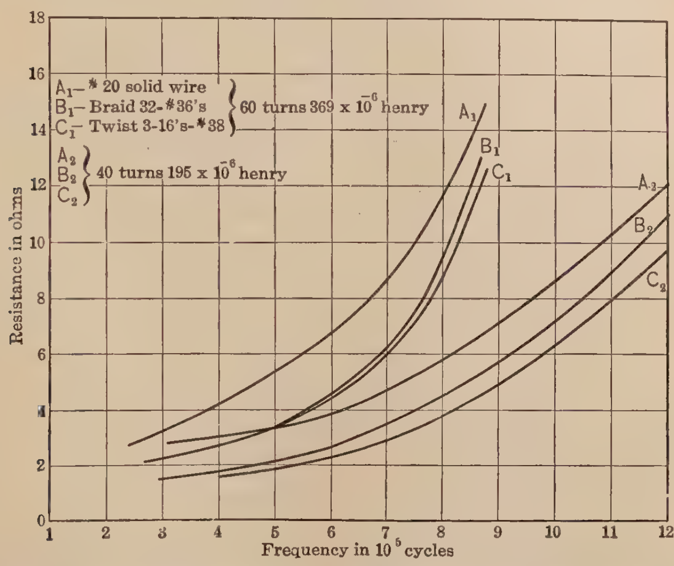

FIG. 28.—Typical resistance curves of solid wire coils and cable-wound coils. All coils were single layer solenoids of about 4 inches diameter.

It can be seen that for both sets of coils (one set having 60 turns in each coil and the other set 40 turns in each coil) the cable coils show a lower resistance than those using solid wire. For both sets of coils the resistance of continuous currents was practically the same for cable as for solid wire.

In Fig 29 are shown resistance curves for coils of greater inductance than those of Fig. 28; coil A was of solid wire and the other two were of cable. It can be seen that coils A and C had practically the same resistance for continuous current but at a comparatively low frequency (200 kc.) the solid wire coil had twice the

resistance of the cable coil. For the higher frequency the solid wire coil continues to have much higher resistance than the cable.

For very high frequencies cable coils show as high resistance as, or even higher than, the solid wire, and for these frequencies (about 2000 kc.) it does not pay to use cable. Fig. 30 shows the comparative resistances of coils suitable for the high frequencies. Those with the subscript 3 are suitable for frequencies as high as 10,000

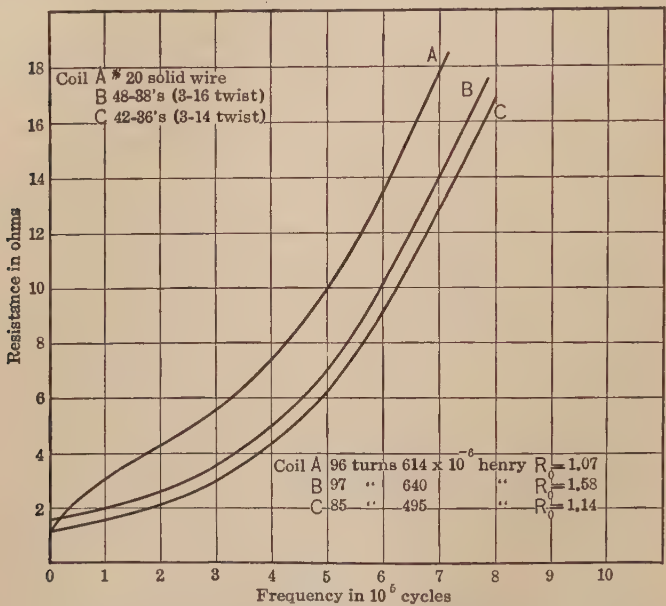

FIG. 29.—Showing solid wire coil better than cable coils, at very low frequencies, and worse at higher frequencies.

kc. For these very high frequencies solid wire, about No. 10 size, is best used for the coils.

16. Fixed Condensers Used in Radio.—A fixed condenser is one with a fixed value of capacity; it is not suitable for tuning a circuit to resonance but is useful for several other purposes in radio sets.

We may say in general that a fixed condenser is used to *by-pass* the alternating current around some part of the radio set where continuous current is desired and alternating current not desired. Thus the B battery of a radio receiver is generally shunted by a

fixed condenser. Whatever alternating current there may be in the plate circuit of the vacuum tubes (this is where the B battery is used) will then be shunted away from the B battery. Thus in Fig. 31 the condenser C serves as a by-pass around both the telephone receivers and the B battery.

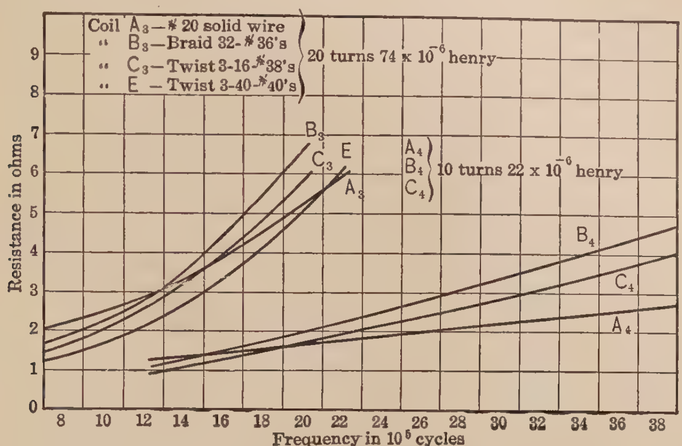

FIG. 30.—Showing that at very high frequencies solid wire coils again become superior to cable coils.

A fixed condenser is generally made of thin metal sheets separated by sheets of paper which have been impregnated with oil or wax. Fig. 14, p. 34, shows the construction of one of these condensers.

Such a condenser has two, three, four or even more sheets of paper between the sheets of tin foil or aluminum foil depending upon the voltage of the circuit it is intended for. Using high-grade paper 0.0005-inch thick, properly impregnated with wax, we may say roughly that one layer of paper should be used for every hundred volts of the circuit. Thus if the voltage across the condenser is to be 400 a four paper condenser is suitable. Such a condenser may stand 1000 volts for a few minutes without breaking down but practice shows that a

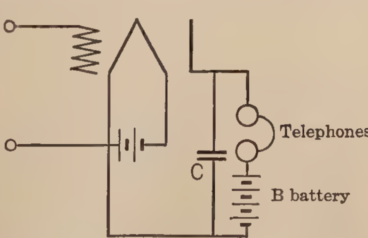

FIG. 31.—Showing one use of a fixed condenser, used to bypass the radio frequency ripples of the plate current around the phones.

large factor of safety should be allowed, as the dielectric strength of a condenser of this type seems to decrease with age.

When new a good waxed paper condenser should show an insulation resistance of about 1000 megohms for the one microfarad size; for smaller capacities it will be higher, and vice versa.

Instead of oiled or waxed paper, mica may be used for the dielectric. The mica is a much better insulator than paper and more durable but of course is more expensive and is never used unless the voltage is so high that the wax impregnated type will not "stand up."

The capacity of these by-pass condensers can be calculated by eq. 16, p. 35. For paraffin wax or oiled paper the k of this formula is about 2.2; a special wax having a k of about 4 has been much used for radio condensers but it is not as dependable as the oil or paraffin wax, seeming to deteriorate greatly with age.

17. Variable Condensers.—A variable condenser is always used to tune the radio frequency circuits of a receiving set. The general method of construction is shown in Fig. 13, p. 33; this is a type of standard variable condenser used for laboratory measurements and the mechanical features of its construction are much more precise than is necessary for ordinary tuning purposes.

It is present practice to "gang" the several tuning condensers of a set; for such use the most important characteristic of a condenser is mechanical ruggedness. If, due to a jar, the plates of one of the series of condensers become appreciably bent or displaced, the response of the set for a given signal may be decreased to a small fraction of its normal value. The amount of solid dielectric (hard rubber, isolantite, or similar substance) used in its construction should be small and, further, it should be so placed that it is in as weak an electric field as possible. It can be seen that the condenser of Fig. 13 satisfies these requirements.

If the stationary plates of the condenser are semicircular and the rotating plates are of the same form, the condenser is called a **straight line capacity** condenser. This is the type generally useful in laboratory measurements.

For use in wave meters (see section 8, p. 50) it is desirable to form the plates of the condenser in such a way that as the movable plates are turned the circuit tunes for the different wave lengths with an approximately uniform wave-length scale. The stationary plates of such a condenser (called a **straight-line wave-**

length condenser) are generally of semicircular shape and the rotor plates have a special form.

In another type, called the **straight-line frequency condenser,** the stationary plates are generally semicircular and the movable

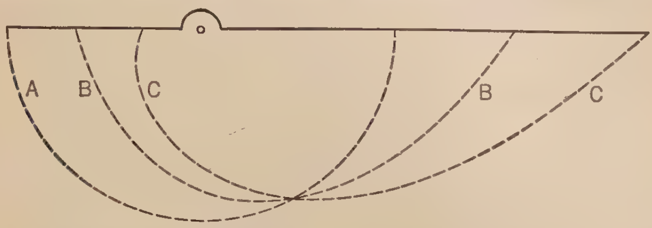

FIG. 32.—Showing the approximate plate forms of straight-line capacity, straight-line wave length, and straight-line frequency condensers.

plates are somewhat more distorted in form than those of the straight-line wave-length condenser. In Fig. 32 are shown the approximate forms of rotor plates for the three types, *SLC*, *SLW*,

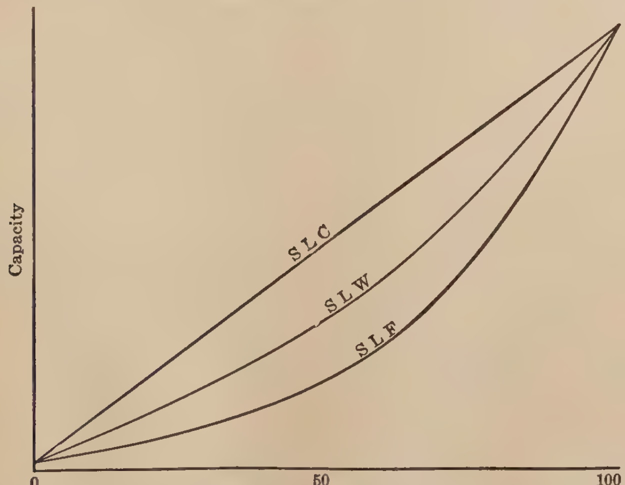

FIG. 33.—Approximate forms of capacity-variation curves for the three condensers of Fig. 32.

and *SLF* condensers. These three condensers would all have the same total capacity, but the variation of capacity with the angle of rotation is different for the three. In Fig. 33 are shown approximate forms of the capacity curves for the three types, plotted

against the angle of rotation. The exact form of the curves *SLW* and *SLF* depends somewhat upon the amount of stray capacity in the set itself, wiring, vacuum-tube capacity, etc.

18. Losses in a Condenser. Shunt and Series Resistance.—In a condenser used at radio frequencies the actual heat losses in the plates are appreciable and of course the dielectric used to separate the two sets of plates produces some power loss.

The total loss in a condenser may be expressed in terms of power factor, just as for a coil. For a good modern variable condenser used in the tuned circuits, the power factor at 1000 kc. is about 0.003. This means that the **equivalent series resistance** of the condenser is 0.3 per cent of its reactance. The angle whose cosine is 0.003 is about 89° 50′ and we see that the current flowing into the condenser leads the voltage by this angle.

Thus a condenser of 0.0005μf at 1000 kc. has a reactance of 319 ohms; its equivalent series resistance is then 319 × 0.003 = 1 ohm approximately. This is for a good condenser; a poorly constructed one might have several times this value of resistance.

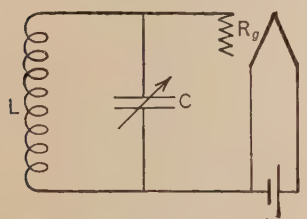

FIG. 34.—Showing one case of a resonant circuit with a resistance shunting the condenser.

There is sometimes a resistance shunting a condenser, as shown in Fig. 34; here the input circuit of the vacuum tube, grid to filament, is connected in parallel with the tuning condenser *C*. This shunt resistance, *Rg*, must be changed into an equivalent series resistance before its effect on the tuning of the circuit can be estimated. A shunt resistance R_{sh} can be changed to an equivalent series resistance, R_s by the relation

$$R_s = \frac{X_c^2}{R_{sh}} = \frac{1}{(2\pi fC)^2 R_{sh}}. \quad \ldots \ldots \quad (38)$$

The series resistance so found is to be added to the resistance of the coil, to obtain the resistance of the circuit. It may be that in addition to the shunt resistance of the condenser there is a series resistance to the condenser due to the resistance of its plates, connections, dielectric loss, etc. In this case the R_s obtained from eq. 38 is to be added to the sum of the coil resistance and the series resistance of the condenser.

As an example we will suppose that the coil of Fig. 34 has 12 ohms resistance, that the condenser C has a capacity of $0.0003\mu f$, that the losses in its plates and the bakelite blocks used in its construction give it a series resistance of 2 ohms, that the frequency impressed on the circuit is 1000 kc. and that the resistance Rg, between the grid and filament of the vacuum tube, is 100,000 ohms. What is the total equivalent series resistance of the circuit, and what is the decrement of the circuit?

We first use eq. 38 to change the shunt resistance Rg into its equivalent series resistance

$$R_s = \frac{1}{(2\pi \times 10^6 \times 3 \times 10^{-10})^2 \times 10^5} = 2.8 \text{ ohms.}$$

Total resistance is therefore $12 + 2 + 2.8 = 16.8$ ohms.

If the frequency is 1000 kc. and capacity is $0.0003\mu f$ the inductance (from eq. 27) is $82\mu h$.

Then the decrement, from eq. 29, is

$$\delta = \frac{R}{2f_rL} = \frac{16.8}{2 \times 10^6 \times 82 \times 10^{-6}} = 0.103$$

It will be noticed from eq. 38 that the equivalent series resistance rises rapidly as the capacity of the condenser is diminished, that is, when the circuit is tuned for the higher frequencies. This is the reason that most radio sets are much less selective for the higher broadcast frequencies than for the lower ones.

Taking into account all of the losses in circuits so far discussed, also losses in the vacuum-tube socket (two terminals of which are connected to the tuning condenser), and losses in wiring, etc., it will be found that the decrement of the radio-frequency circuits of an average good radio receiver is from 3 to 6 per cent, generally being higher for the higher frequencies.

19. Use of Wave Traps to Diminish Interference.—It has been shown how resonance is utilized in radio circuits to "bring in" a desired signal; it is also possible to use this same action to eliminate an undesired signal.

In Fig. 35 is shown one element of a radio receiver, the antenna and the first tuned circuit connecting to a vacuum tube. The L_1–C_1 circuit is always tuned to (brought into resonance with) the desired signal, and frequently the antenna capacity, C_1, and its inductance L_1 are made to resonate to the same frequency.

It may be that an undesired signal is of nearly the same frequency as the desired signal, and much louder because of the proximity of the transmitting station. Such a strong signal produces **interference** with the desired signal. To reduce this interference two schemes have been much used. A coil and variable condenser in series are connected from point *A* of the antenna to ground, as shown by the dotted line. By tuning this circuit to the undesired frequency its impedance is made much lower than that of coil *L* so that practically all of the interfering signal is by-passed to

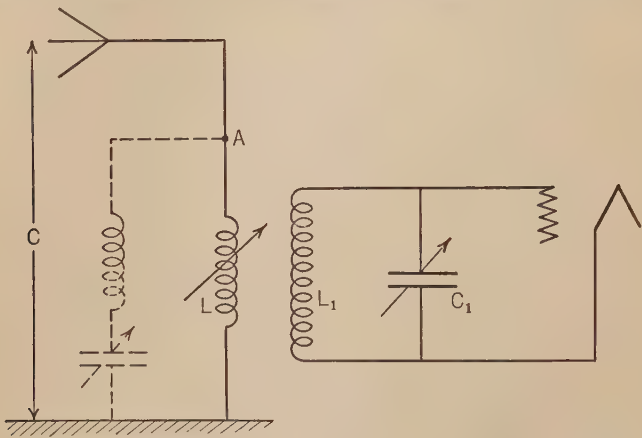

FIG. 35.—The series resonant circuit shown by the dashed lines is a *wave trap*, designed to pass some undesired current around the coil *L*. The trap is tuned to the undesired frequency.

ground and does not get into the receiving set. A combination of coil and condenser so used is called a **wave trap.**

Sometimes the antenna is opened at *A* and the wave trap inserted in series with the antenna at this point. In such a case the wave trap consists of a coil and condenser in parallel, adjusted for resonance with the undesired signals. As shown in section 12 of this chapter such a parallel resonant circuit offers very high impedance to the current for which it is tuned and a much smaller one to other frequencies. Thus but little of the undesired signal current will flow in the antenna circuit whereas the desired signal current is but little interfered with.

20. Free Oscillations in Radio Circuits.—The alternating currents which ordinarily flow in the tuned circuits of a radio receiver

are caused to flow by the voltages set up in the antenna circuit by the signal being received. They are called **forced currents** or more generally **forced oscillations.** Their frequency is exactly that of the signal voltage and they increase and decrease in intensity exactly as the signal voltage in the antenna increases and decreases in intensity.

There are other alternating currents set up in the tuned circuits of a receiver (and a transmitter also to some extent) which are called **free oscillations.** Thus if a lightning flash occurs within many miles of an antenna it gives an electric "shock" to the antenna. This shock has no frequency because it is generally a

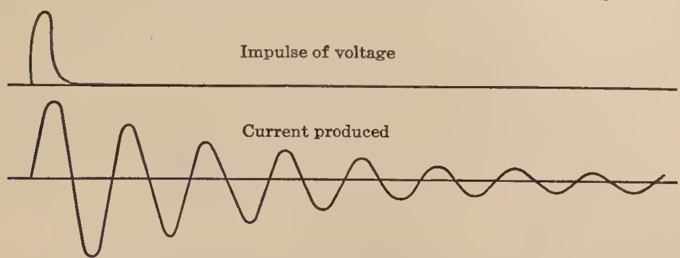

FIG. 36.—A pulse of voltage sets up in a resonant circuit a damped sine wave of current, of frequency equal to the resonant frequency of the circuit.

uni-directional voltage, that is, it is a voltage of very short duration acting either up or down in the antenna circuit. Voltages of this kind give crackling noises in the loud speaker of the radio set; they go under the name of **static.**

Such impulsive voltages set up alternating currents in the antenna and other tuned circuits of the radio set and these currents have a frequency the same as the **natural frequency** of the tuned circuit. This natural frequency is practically that for which the circuit is tuned, that is, equal to $\frac{1}{2\pi\sqrt{LC}}$. These free oscillations rapidly die away and have approximately the form given in Fig. 36, where the **aperiodic voltage** or **voltage pulse** is shown in the upper part of the diagram and the resulting **damped oscillatory current** is shown below.

The duration of the oscillatory current depends upon the decrement of the circuit. If we agree that the oscillatory current ceases when its amplitude has fallen to 1 per cent of its maximum amplitude (of course theoretically these oscillatory currents last

forever when they are once started) then the number of cycles of current is approximately given by the formula

$$N = \frac{4.6 + \delta}{\delta}, \quad \ldots \ldots \quad (39)$$

where δ is the decrement of the circuit $= \dfrac{R}{2f_rL}$.

21. Selectivity of a Receiver for Free Oscillations.—A little thought will then show why atmospheric disturbance, or static, interferes with signal currents no matter to what frequency the set is tuned. The static voltage always sets up currents of that frequency for which the set is tuned; they are thus amplified and reproduced in the speaker the same as is the signal current for which the set is tuned.

The remarks made above regarding pulses of voltage hold good to a considerable degree for the signals sent off from spark transmitters, such as are generally used on merchant ships. It will be found that radio sets near a harbor "pick up" ships' signals all over the broadcast range of the receiver; that is, 600 to 1500 kc., although the ships' signals are always 500 kc. or even lower.

22. Effect on Resistance and Reactance of a Circuit, of Another Circuit Coupled to It.—In radio practice we continually meet the situation where one circuit is coupled to another, generally magnetically, and the question at once arises as to what effect the second circuit has on the effective resistance and reactance of the first. A complete analysis is beyond the scope of this text, so we give here merely the conclusions of such analysis.

The effective resistance of the first circuit is always increased by the presence of the second, but the reactance may be either increased or decreased, or may even change from inductive to capacitive, or vice versa.

Consider the generally encountered case, where a circuit having capacity, resistance, and inductance in series, is magnetically coupled to a coil in another circuit; this is illustrated in Fig. 37. Calling R'_1 and X'_1 the effective resistance and reactance of circuit 1, analysis yields the two equations.

$$R'_1 = R_1 + \left(\frac{\omega M}{Z_2}\right)^2 R_2. \quad \ldots \ldots \quad (40)$$

$$X'_1 = X_1 - \left(\frac{\omega M}{Z_2}\right)^2 X_2. \quad \ldots \ldots \quad (41)$$

If the frequency impressed on the first circuit happens to be the resonant frequency of the second (as is frequently the case) surprising results, with regard to resistance, may be obtained. Thus let us suppose that coil L_1 (of Fig. 37) is in the plate circuit of one of the amplifying tubes of a radio set, and that the L_2–C_2 circuit of Fig. 37 is the tuned radio-frequency circuit connected to the input circuit of the next tube. How will the X and R of coil L, be affected by the presence of the coupled tuned circuit?

As typical values we take $L_1 = 20\mu h$, $R_1 = 2$ ohms, $L_2 = 250\mu h$, $C_2 = 0.000150\mu f$, $R_2 = 15$ ohms and the coefficient of coupling between L_1 and L_2 is 50 per cent.

The term "coefficient of coupling" is used to idicate how intimately the two coils L_1 and L_2 are associated magnetically. When

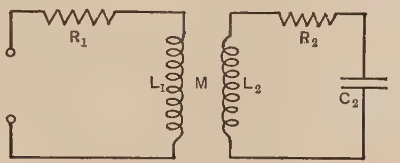

FIG. 37.—A second circuit, if tuned to the frequency impressed on the first circuit (to which the second is coupled) may increase the apparent resistance of the first circuit to a surprisingly large value.

one coil is wound as intimately as possible with the other the coefficient of coupling is nearly 100 per cent; as the two coils are placed farther apart, so that only a small part of the magnetic field of the first links with the turns of the second, the coupling becomes weak. Quantitatively the coefficient of coupling is given by the relation

$$K = \frac{M}{\sqrt{L_1 L_2}}, \quad \ldots \ldots \quad (42)$$

from which

$$M = K\sqrt{L_1 L_2}, \quad \ldots \ldots \quad (43)$$

in which K = coefficient of coupling;

M = coefficient of mutual induction between the two inductances L_1 and L_2.

In the problem above

$$M = 0.5\sqrt{250 \times 20} = 35.4\mu h.$$

If the frequency impressed on the primary circuit is the resonant frequency for the second circuit we must have

$$f = \frac{1}{2\pi\sqrt{L_2C_2}}$$

or

$$\omega = \frac{1}{\sqrt{L_2C_2}}$$

Substituting the values of L_2 and C_2 given we find that $\omega = 5.17 \times 10^6$. For such a frequency we evidently have no reactance in the second circuit so that $Z_2 = R_2 = 15$ ohms.

Then from eq. 40.

$$R'_1 = 2 + \frac{(5.17 \times 10^6 \times 35.4 \times 10^{-6})^2}{15} = 2 + 2230 = 2232 \text{ ohms}$$

Thus, although the coil L_1 has a real resistance of its own of only 2 ohms, it acts towards the plate circuit of the vacuum tube as though it had 2232 ohms.

For this special frequency the reactance of coil L_1 is not changed from its true value, because $X_2 = 0$ and so eq. 41 yields the relations that $X'_1 = X_1$.

CHAPTER III

GENERAL IDEA OF RADIO COMMUNICATION

1. What is Radiated Power?—In general, electric power is transmitted over wires; these wires may be large enough to convey hundreds of thousands of kilowatts a hundred miles or more or may be the small wires of an ocean cable carrying a small fraction of one watt of power several thousand miles. In either case the wires serve to confine the electrical energy and guide it from one place to another. The frequency of current used is always comparatively low; for example, the ocean cable current may be about 15 cycles per second, the high-powered circuit perhaps 25 cycles per second, and a long telephone line possibly up to 3000 cycles per second. For frequencies as high as these practically all of the electric energy sent from the transmitting station reaches the receiving station except that wasted as heat as it travels along the wire.

If the frequency of the current is increased greatly it will be found that some of the electric energy shakes loose from the circuit and escapes into space, never returning to the circuit; this is called **radiated power.** After escaping from the circuit it travels in all directions in space, much as the energy from an electric lamp, in the form of light waves, travels from the lamp in all directions.

There are many examples of radiated power all around us; the music of an orchestra reaches its listeners by the radiation of energy in the form of sound waves, and the heat and light from the sun both reach us as radiated energy, in the form of electro-magnetic waves.

2. Dependence of Radiated Power on Frequency.—Our submarines have built into their hulls a large flat flexible steel diaphragm which can be vibrated back and forth by electrical means. Its vibrations send off sound waves into the ocean and the energy of these sound waves can be measured. If, keeping the other conditions of the vibrating system the same, the frequency is varied,

it will be found that the energy radiated into the ocean as sound waves varies as the square of the frequency, that is, doubling the frequency increases the radiated power to four times its value.

Any wire carrying alternating current radiates some power in the form of electric waves; for ordinary frequencies and forms of electric circuits the amount of power thus sent out is too minute to be measured. But if the frequency is increased, keeping the current constant, more and more energy is radiated until when the frequency is a million or more the radiated power may be detected at great distances.

Simple experiments convince us, then, that to radiate much power the frequency must be high; and careful experiment would yield the result that, for a given current, *the power radiated from a given circuit varies as the square of the frequency.*

Furthermore if the frequency is held constant and the current is varied it may be found as the result of measurement that *the radiated power varies as the square of the current,* and so we reach the conclusion that

$$\text{Radiated power} = KI^2f^2, \qquad \ldots \ldots \qquad (44)$$

in which K is a factor depending upon the shape of the circuit from which the power is being radiated.

3. Dependence of Radiation upon Antenna Shape.—From experiment it can be found that a straight vertical wire is the most efficient form of electric circuit from which to radiate power. It will be found, however, that only a comparatively small current can be made to flow in such a circuit; as the current is forced to increase by impressing more voltage on the circuit a blue glow, called **corona,** appears at the tip of the wire and causes large energy losses. The vertical wire is called an **antenna.**

To permit larger currents in the vertical wire, without trouble from corona, it has been found best to connect the top end of the vertical wire to a flat network of wires suspended horizontally at the same height as the top of the vertical wire. This overhead network of wires really forms one plate of a large condenser, the earth being the other plate. The vertical wire then becomes the connecting wire for the top plate of the condenser. Evidently the larger the overhead network of wires the greater is the capacity of the condenser; and hence, for a fixed frequency and voltage, the larger is its charging current, which flows in the vertical wire.

As the frequency at which the antenna is to be used is raised, smaller and smaller overhead networks can be used; for broadcast stations the overhead network frequently reduces to one comparatively short horizontal wire, with the vertical wire connected to its middle point. For frequencies higher than the broadcast band even this small overhead structure must be eliminated so that for frequencies of 10,000 kc. and more a simple vertical wire is used as antenna.

In general we may say that the more an antenna approaches in shape the simple vertical rod the more efficient it is as a radiator of power, for a given frequency and current.

4. Radio Waves. Wave Length and Frequency.—Let us consider first the simplest possible antenna, as illustrated in Fig. 38. A vertical wire is cut in the middle and a high-frequency alternator is connected in at this point. The two halves of the wire, *B–C* and *D–F*, constitute two plates of a condenser and the alternator *A* serves to furnish this condenser with charging current. The magnitude of the charging current will be a maximum at the alternator terminals and will diminish along the two wires, being of course zero at the two free ends. This high-frequency current will set up electric and magnetic fields in the space surrounding the antenna, the general form and disposition of these lines being as shown in Fig. 39. Both magnetic and electric lines reverse as the current reverses, and if this reversal takes place at a high-frequency part of the energy represented by the electric and magnetic fields is "shaken loose" from the antenna and goes off into space, traveling as *electro-magnetic waves.*

FIG. 38.—An ideal radiating system is a vertical wire, with the high-frequency alternator (generally a vacuum tube) connected at its mid-point.

As the word indicates, such waves are made up of a combination of electric and magnetic fields; both kinds of fields are necessary and always present in electro-magnetic waves, or radio waves. Of course we cannot see these waves because our eyes cannot see either electric or magnetic fields; moreover, even if we could see such fields, we could not see the electro-magnetic waves because these travel with such a high velocity, practically at the same speed as light. This is 186,000

miles a second in English measure or 300,000 kilometers a second in the metric system.

In an actual antenna, two wires, such as *B–C* and *D–F* of Fig. 39, are seldom used; only the upper one is used. The surface of the earth serves as the other plate of the condenser, as indicated in Fig. 40. It will be noticed that the magnetic field is parallel to the earth's surface and the electric field is perpendicular to the earth's surface. When the current in the antenna is reversed the

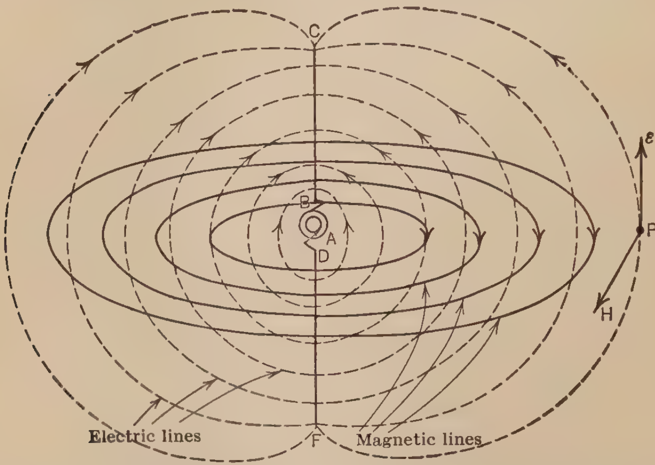

Fig. 39.—The magnetic and electric fields set up around the radiator of Fig. 38 have about the distribution shown here.

electric and magnetic fields both reverse from the direction shown in Fig. 40.

For one complete cycle of current in the antenna one wave is radiated; this wave then must consist of two parts, one with the electric and magnetic fields in the same direction as in Fig. 40, and one with them reversed. If these radiated waves travel out over the earth's surface from the antenna with a velocity V and the number sent out per second is f, the frequency of the current in the antenna, it follows that the length of one radiated wave, λ, is obtainable from the relation

$$V = f\lambda \quad \text{or} \quad \lambda = V/f. \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

In radio communication wave length is measured in meters;

the English system of units is not used. As the velocity of wave travel is 300,000,000 meters per second, we have the relation

$$\lambda, \text{ in meters} = \frac{3 \times 10^8}{f}. \qquad (46)$$

In Fig. 41 there is pictured a cross-section of a radio wave traveling over the earth's surface, and the length of a wave is indicated. If the frequency of current in the transmitting antenna from which

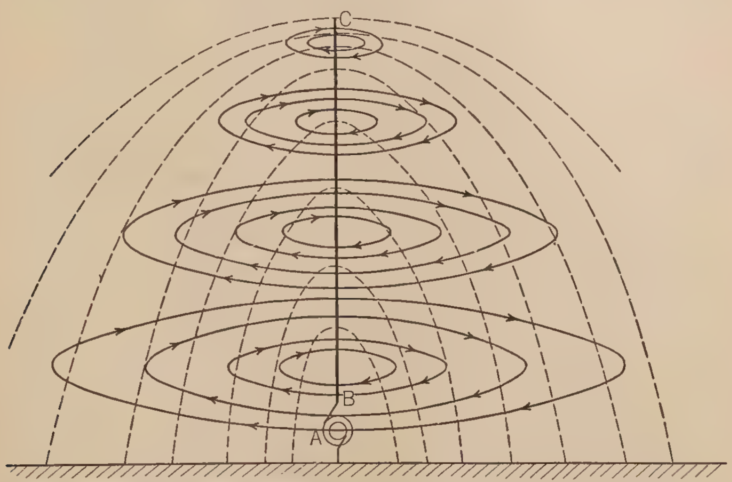

FIG. 40.—In the case of a vertical, grounded, antenna the magnetic and electric lines of force have the form and distribution shown by the solid and broken lines respectively.

the wave came was 1000 kc., the wave length would be, from eq. 46, 300 meters, an ordinary wave length in radio broadcasting.

5. Types of Waves Used in Radio.—According to the scheme of communication being used, different types of radio waves are sent off from the transmitting antenna. In the dot and dash scheme of telegraphy used by most naval vessels the antenna is connected to its source of high-frequency power as long as the key is held down, so the waves radiated have the form shown in *a* of Fig. 42. If the frequency is 500 kc. and the dot and dash are 0.1 second and 0.3 second long respectively, there would be 50,000 waves per dot and 150,000 waves per dash. This is known as **continuous wave** (C.W.) telegraphy. In the merchant marine

damped-wave, or **spark,** telegraphy is generally used. In this scheme the antenna sends off a series of damped-wave trains for each dot or dash. There are generally 1000 wave trains per second, so the dot consists of 100 wave trains and dash of 300 wave

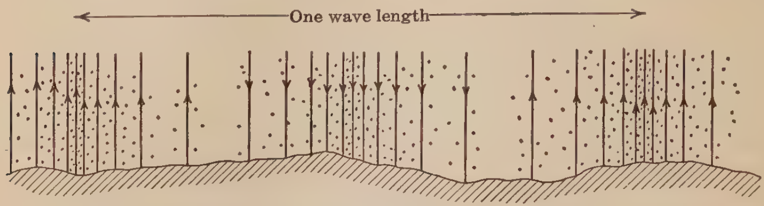

Fig. 41.—After the electro-magnetic wave has traveled some distance from the antenna the electric and magnetic fields near the earth's surface have about this distribution. Electric lines are vertical and magnetic lines horizontal. Direction of magnetic field reverses where direction of electric field reverses. Actually the electric lines lean a few degrees forward of the vertical position, due to the resistance of the earth.

trains. Each wave train dies out before the next one is ready to start, as shown at *b* of Fig. 42.

In the **interrupted continuous wave** (I.C.W.) scheme of telegraphy each dot and dash consists of a group of continuous-wave

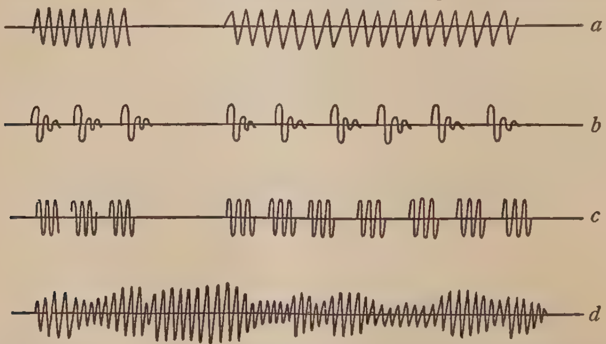

Fig. 42.—Showing the types of waves used in radio communication, continuous-wave, spark-wave, interrupted continuous-wave, and modulated continuous-wave radiation are all used today.

signals, as shown at *c* of Fig. 42. The high-frequency power supply furnishes continuous waves to the antenna in groups, perhaps 500 groups per second. A dot would then consist of 50 groups and a dash of 150 groups of continuous waves. The time between groups is about the same as the duration of one group; if the fre-

quency is 500 kc. each group of continuous waves would consist of 500 waves. This scheme is much the same as spark telegraphy, with the difference, however, that the amplitude of the waves of one group is approximately constant whereas in spark telegraphy it starts high and dies to zero in a comparatively short time

In the fourth scheme of radio communication, **radio telephony,** the antenna is connected to the source of continuous wave power continually but the apparatus is so arranged that the amplitude of the continuous wave follows an envelope which corresponds to the sound wave of the voice or music. Such a signal looks like that of *d*, Fig. 42. It is known as a *voice-modulated wave.*

6. Propagation of Radio Waves. Attenuation.—As the radio waves travel out from the transmitting antenna they decrease in intensity very rapidly at first and then more slowly. The action is much the same as occurs when a pebble is dropped into a quiet pool of water. Immediately around the place where the pebble strikes the water comparatively large waves are set up; as these travel out in concentric circles of ever-increasing radius the *height* of the wave (which corresponds to the *intensity* of the radio wave) continually diminishes.

Even if there was no waste of energy as the wave travels over the earth's surface its intensity must diminish because of the ever-increasing length of the wave front. The length of the wave front is evidently the circumference of a circle having the transmitting antenna as a center; as the radius of the circle increases, so does its circumference. As the energy of the wave then has to spread itself over an ever-increasing length of wave the intensity of the energy at any one point must evidently diminish.

There is, however, an additional reason for the diminution in intensity of radio waves as they travel away from the transmitting station. Some of their energy is wasted in the surface of the earth, some in trees and buildings, and some travels upward from the earth's surface. These combined effects make the average signal fall off much faster than in direct proportion to the distance from the transmitter; the exact law for diminution is different for different seasons, localities, land or ocean and many other factors. It cannot be predicted but must be measured; if the law is determined from measurements made in the summer it will not be correct for the winter season and the law is entirely different for night than for day time.

7. Frequencies Used in Broadcasting.—Some years ago it was realized that if great confusion was not to be caused in radio communication international agreement must be reached regarding the frequencies to be used for different purposes. Marine communication is the most important service that radio is carrying on; ship to shore and ship to ship communication can be carried on only by radio and hence this service must receive first consideration in the assignment of frequencies, or wave length. For merchantship traffic 600 meters was adopted as the standard wave length. This wave length is short enough to be radiated efficiently from such an antenna as can readily be erected on a ship's spars and not so short as to be subject to the great vagaries encountered with waves of 200 meters and less. For the trans-oceanic radio channels wave lengths from 5000 to 20,000 meters are used. For naval vessels wave lengths from 750 meters up to a few thousand find application.

Radio broadcasting was the last service to be developed, it was made to fit into the scheme by using wave lengths from 550 meters down to 200 meters. This wave length range, about three to one, is as great as can be tuned without using more than one set of inductances, as was explained in Section 14, p. 60.

The normal frequency band for broadcasting purposes is then from 550 to 1500 kilocycles. Several of the more important broadcasting stations send out their programs on one or more short waves, as well as their normal wave. For instance, a station sending on 360 meters may also send on 40 meters; this short-wave transmission is primarily for studying the behavior of these very high frequencies.

8. Short Waves and Their Behavior.—We may call any waves of length less than 100 meters short waves, although generally the tendency is to apply that term only to waves of 50 meters or less. The laws of propagation for these waves are most unusual and for many years it was assumed that such short waves were valueless for purposes of reliable communication. Occasionally short-wave stations, of low power, were heard over great distances, but such occurrences were classified as "freak transmission."

As a result of the work of many experimenters, however, it has been found that these short waves follow certain laws with reasonable consistency, but these laws are of a most peculiar nature. As the receiving set is moved away from the short wave transmitting

station the received signal falls off very rapidly and in a comparatively few miles dies out altogether, even though the station may be sending out kilowatts of power. There is then a zone of silence, extending for a distance of hundreds of miles. When the receiver has been moved perhaps 1000 miles away from the transmitter the signal is again picked up and for perhaps 5000 miles is heard with plenty of intensity.

The behavior of these waves is shown by the peculiar curve of

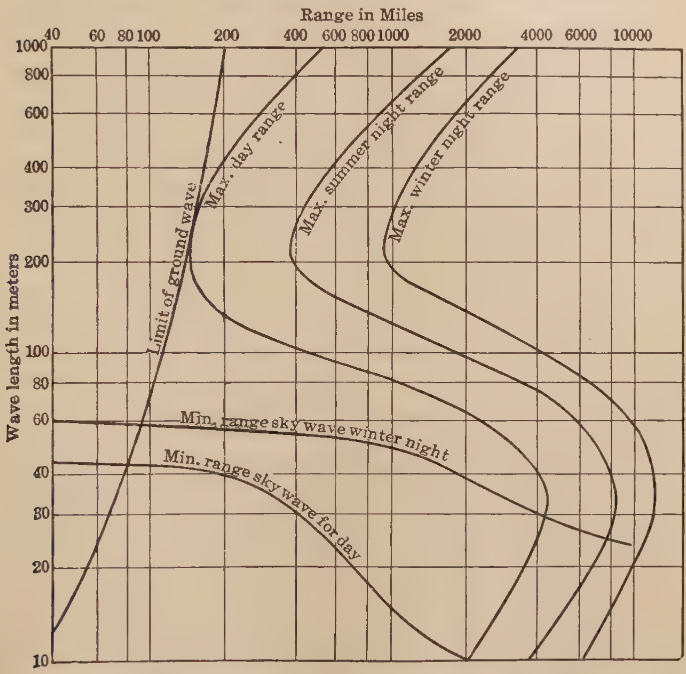

FIG. 43.—Showing the propagation characteristics of high frequency radio waves.

Fig. 43. These curves are not theoretical, but follow from the results of experiment. They represent the average of many thousands of observations. A 5-kw. transmitter has been assumed and it has been also assumed that at the receiver we require a signal strength of 10 microvolts per meter to obtain an audible signal.

We first notice the curve "Limit of ground wave." This tells us that if the transmitter is sending out a 100-meter wave we shall hear it as we move the receiver away from the transmitter for 125

miles. If 40 meters is used we can hear it only 75 miles and if 1000 meters is used we shall hear it 200 miles. Past these distances the signals become inaudible.

If the receiver is carried still farther away from the transmitter all these signals reappear, at distances varying with the wave length, time of day, and season of year.

The 40-meter wave, for example, would again be picked up, at a distance of 200 miles, if we are listening in the day time, or at a distance of 1900 miles if we are listening on a winter night. These values are picked off from the intersection of the "40-meter" line with the curves labeled "Min. range sky wave for day" and "Min. range sky wave winter night" respectively. On the winter night we should continue to hear the signal from the 1900-mile point until we reach a distance of about 12,000 miles from the station.

Listening to a 20-meter wave in the day time, we would lose the signal at a distance of 55 miles from the station; it would reappear when the receiver has been moved 700 miles from the transmitter and from here the signal would be audible until a distance of 3500 miles had been reached. And if we happened to be listening on a winter night we could hear the station up to a distance of 10,000 miles.

The zone of silence extending from 55 miles (for the 20-meter wave) to 700 miles, is called the "skip distance" of the signal.

9. Kennelly-Heaviside Layer.—The peculiar action of these short waves is attributed to a layer of rarefied air (made partially

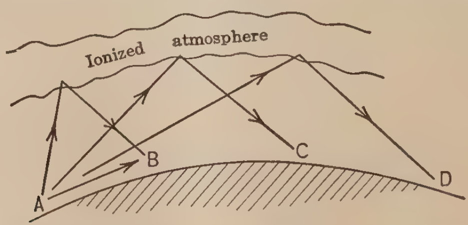

FIG. 44.—Short waves are reflected by a layer of ionized atmosphere, located about 100 miles above the earth's surface.

conductive by the sun's rays) apparently located 100 to 200 miles above the earth's surface.

Radio waves are reflected from a conducting surface, just as light waves are reflected from a shiny metallic surface. This layer of semi-conducting, or "ionized," air surrounds the earth as sug-

gested in Fig. 44. A transmitting station located at A sends waves along the earth's surface and this is called the *ground wave;* it also sends waves upward and these, striking this ionized layer of air, are reflected downward as suggested at B, C and D; it is these waves which have been reflected down from the sky (called "sky waves") which account for the extraordinary transmission distances of some of the short wave stations.

The probable existence of this layer of conducting air, and its behavior, were suggested by Kennelly and Heaviside and so it has come to be known as the Kennelly-Heaviside layer.

10. Absorption of Radio Waves by Groups of Steel Buildings.—In the early days of broadcasting it was the custom to locate the

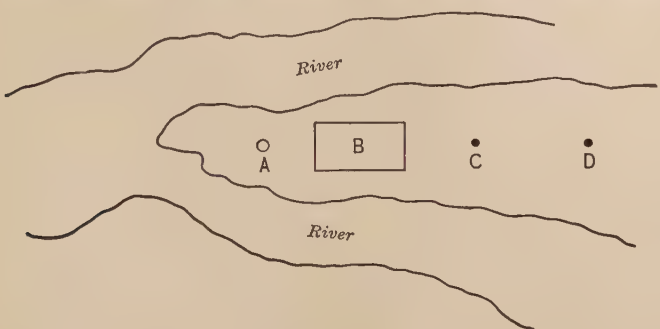

FIG. 45.—Diagram of New York City; a signal originating at A is nearly absorbed by the steel buildings in district B, resulting in practically no signal at C. At D, farther away from A, in line with C, the signal increases in strength, due to energy flowing into district from the sides.

transmitting stations in the centers of large cities. Certain peculiarities in the transmission soon showed the inadvisability of this procedure, and all of the better grade stations were moved out into the outlying districts of the large cities. Better signal strength, for a much greater number of listeners, resulted from this change of location.

In a city like New York a condition as indicated in Fig. 45 was common. Having the broadcast transmitter at A it would be found that only a few miles away at C the signal was so weak as to be inaudible, but at the more distant point D, a good signal was received. The reason was at once discovered when the station A was made portable and the transmission to point C was measured for different locations of station A.

At B there is a district of tall steel-frame buildings; these, being conductors, absorb large amounts of energy from the radio waves sweeping past them, resulting in a "radio shadow" in region C. The effect is much the same as the "wave shadow" caused by a small island in a lake. Directly in the lee side of the island there are imperceptible waves, but with increasing distance from the island the waves again build up, partly from the wind which has come over the island and partly from the waves on either side of the island rolling into the wave shadow of the island.

A broadcasting station located in a district of tall steel buildings has most of its radiated energy absorbed in the immediate vicinity of the station; this is evidently a very uneconomic arrangement, as the purpose of the station is to reach as many listeners as possible. The modern broadcasting station is therefore located in the country, perhaps 25 miles from the large city; its studio is located in the city for ready accessibility and a "high quality" telephone line connects the studio to the station.

11. Radio Waves Inside Steel Buildings.—In a building having a steel framework very erratic conditions regarding radio receiving are encountered. The steel framework frequently makes a reasonably good shield against the radio waves, permitting but very little of their energy to penetrate into the building.

Ordinarily it is possible with a *loop antenna* to tell the direction of the broadcasting station from the receiver but inside a steel building an attempt to do this may indicate the station to be in a direction exactly opposite to its true direction. With a loop antenna the best signal will generally be received in the building when the loop is placed close to a window. In other cases where one of the principal vertical columns of the steel framework runs through a wall, the best results are obtained by placing the loop antenna as close to this column as possible.

In Fig. 46 are indicated some of the experimental results obtained in a typical steel-frame building; the figures give the measured signal strength in microvolts per meter and the arrows show the apparent direction of the transmitting station. It is practically impossible to predict whether or not an audible radio signal will be obtained in the central part of such a structure.

12. Fading of Radio Waves.—For those who live close to a good broadcasting station the question of *fading* is of no importance, but for the listener a hundred or more miles away from the

station, it is a very vexing experience. With the condition at the transmitting station and receiving station fixed, as regards tuning, power, amplification, etc.; the received signal will wax and wane in strength from a loud signal to one so weak as to be inaudible.

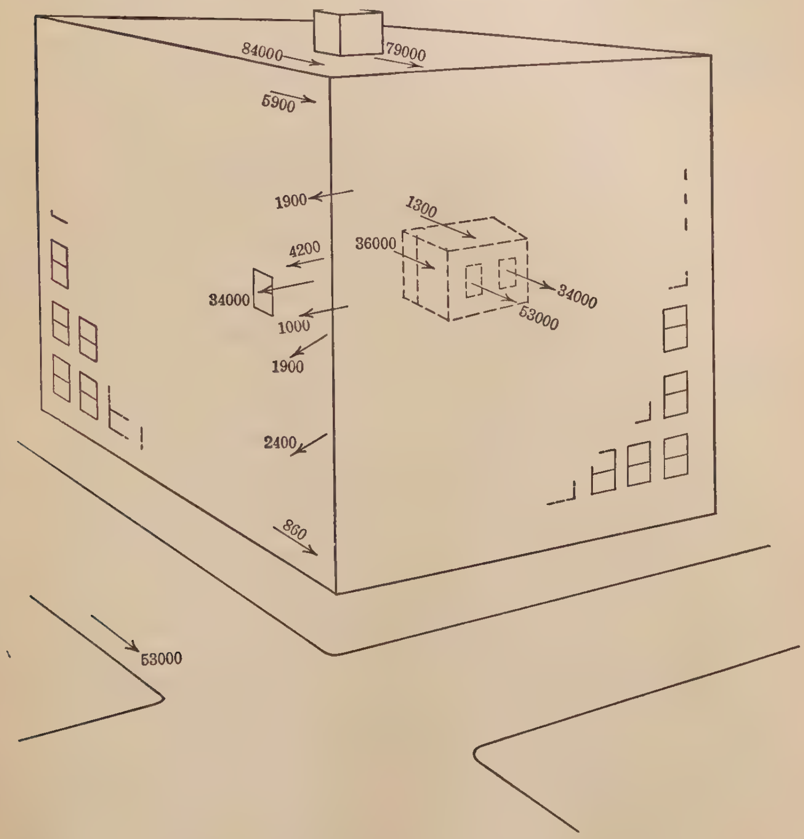

FIG. 46.—Inside of a modern steel frame building the radio waves have surprisingly low strength. On the roof of the building the signal was as great as 84,000 units and inside the building, even close to the outside wall the signal was as low as 860 units, or only 1 per cent of the strength outside the building. Furthermore the direction from which the waves appear to come, inside the buiding, have almost no relation to the actual direction of the transmitting station.

In a general way the difference between day time and night time transmission might be classed as fading, the period of the

fading cycle here being 24 hours. Fig. 47 shows this kind of an effect for a radio telephone channel extending across the Atlantic. The amount of energy received during the day time is small but reasonably uniform. When darkness extends over the whole path a great increase in signal intensity occurs, but also there occur great variations in this intensity. These day-to-night variations are ordinarily not classed as fading, even though they may

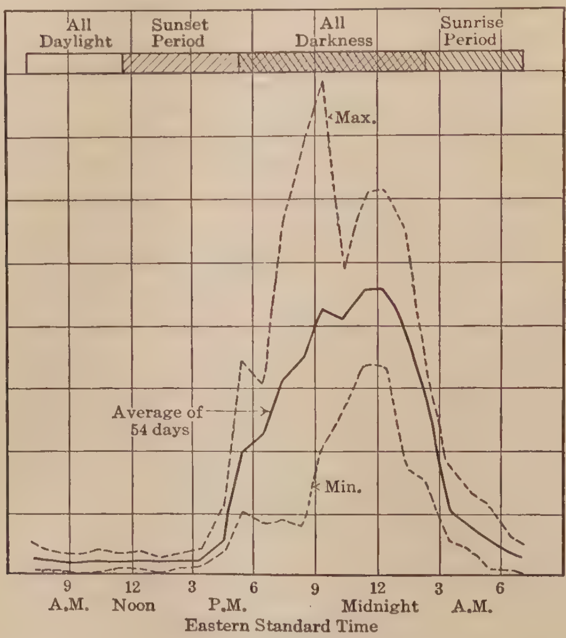

FIG. 47.—Showing how the waves of the Trans-Atlantic radio channel vary in strength during the day.

be caused by the same condition as brings about ordinary fading.

In the ordinary fading phenomenon the waxing and waning of the signal takes place at comparatively short time intervals, perhaps 5 minutes or less. In Fig. 48 there is shown the measured signal intensity (of a station sending out a fixed amount of power) at a receiving station several hundred miles away. There is a reasonably regular fluctuation in the received signal of about 10 to 1 the period being about 5 minutes.

In certain other conditions the fading takes place in such rapid fluctuations as to make the signal sound like a flutter, the period being measured in fractions of a second.

13. Causes of Fading.—It now seems almost sure that fading is not caused to any marked degree by a change in the attenuation of the signal as it travels from transmitter to receiver. The change in the conducting qualities of the intervening air cannot be imag-

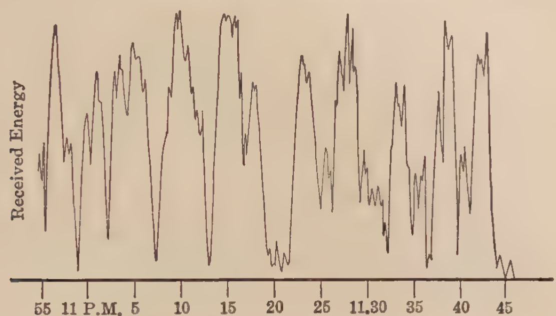

FIG. 48—The kind of fading which takes place in a broadcast radio signal at distances of 100 miles or more from the transmitter.

ined as having such rapid and severe changes in the course of a few minutes.

The results from many experiments indicate almost with certainty that fading is caused by interference between signals which reach the receiver by way of different routes. If the waves which have traveled the two paths arrive at the receiving antenna in the same phase the received signal is intense; but if the difference in length of the two paths is half a wave length, or any other odd number of half wave lengths, the two signals will arrive at the receiver in phase opposition and may practically neutralize one another.

Referring to Fig. 44, p. 84, it is seen that the receiver, at B, will receive one signal direct and the other by reflection from the sky. Under ordinary circumstances within perhaps a hundred miles of the transmitter, the direct signal will be so much stronger than the reflected one that but little difference in signal strength is noticed whatever may be the relative phases.

However if the direct path from A to B is through a district of great absorbing power (a large city of tall steel buildings) then the

signal received at B after reflection from the sky may be as strong as that coming direct. In such a case the change in signal intensity at B may be excessive, but may disappear altogether when the two received signals have phase opposition.

Having this effect in mind it follows that the signal strength at B will vary greatly as the length of the path of the reflected wave changes, this length determining the phase difference of the two signals received at B. If the ionized layer in the sky moves up and down, the length of path for the reflected ray correspondingly changes while that of the ground wave remains the same. The result may be a partial or complete extinction of the signal at B, following the change in phase of the signal coming over the reflecting path.

In certain localities this effect is so marked as to make a radio telephone signal almost unintelligible. The possibility of interference by the two signals depends entirely upon the wave length being considered; as a radio telephone signal uses many frequencies, first one and then another of these disappear (by interference) resulting in a most disagreeable form of distortion. The effect can be remedied only by moving the broadcasting station.

14. Atmospheric and Other Disturbing Waves.—Any rapidly changing electric current sends out radio waves and in many cases these waves are of the kind which cannot be " tuned out " of a receiving set. An electric storm, with its lightning flashes, is the source of very powerful radio waves and if the storm is within a few miles of the receiver these waves will be much more powerful than the waves from any radio station. They produce loud clicks and snaps in the loud speaker. Even when there is no actual storm there frequently are intense electric disturbances in the atmosphere, especially when there are sudden weather changes, and this kind of disturbance frequently produces an almost incessant crackling and hissing noise in the loud speaker.

Disturbing waves, as those mentioned above, are called **static** or **atmospherics.** They constitute the greatest single disturbing factor for the radio engineer to overcome. Being highly damped (they never have more than one or two cycles in a wave train) it is impossible to get rid of them by tuning. And being always present to a greater or less extent, they really set the lower limit of intensity for any radio signal. If the signal gets so weak as to go below the " energy level " of the static, it can never be recov-

ered by amplification or other means. The amplifying means will amplify the static as well as the signal, so the latter always remains hidden in the noise.

There are many other kinds of electric disturbances which frequently are classed as static. Every time a light is turned off or on in the house a click will be heard in the radio receiver. Elevator motors in apartment houses cause much disturbance and such things as electric refrigerators cause a great deal of disturbance in the radio set. The ignition system of an automobile, the motors of a street railway, the charging of electrolytic lightning arresters, etc., all contribute their share to the vast chorus of noises generally heard in a radio receiver, especially in a large city.

15. Types of Antenna Used for Transmitting and Receiving.— At a transmitting station the function of the antenna is to radiate into space kilowatts of power, at a receiving station it is required to pick up only microwatts of power. It will be evident then, that although they may perform their functions, electrically, in exactly the same way, their size and method of construction will be much different.

The transmitting antenna of the ordinary broadcasting station is generally of the T form having a vertical height of from 50 to 200 feet and a length of horizontal top from 100 to 200 feet. It is strongly built and generally suspended between two self-supporting steel towers about 200 feet high. The wires of the antenna are insulated from the steel towers by large porcelain insulators. When the station is operating the voltage on these insulators may be from 10,000 to 50,000 volts.

The overhead wires form one plate of a condenser; the other plate is generally the surface of the earth. As the earth is generally a rather poor conductor a whole network of heavy copper wires is buried in the earth, under the antenna, to improve its conductivity. These *ground wires* are all brought to a common center and the power is supplied to the antenna by using this ground connection and the bottom of the " down lead " (the vertical wire of the antenna) as connections.

Sometimes it is found advisable not to bury the system of ground wires in the earth, but to support them on insulators fastened to the tops of poles 6 to 10 feet high. Such a system of insulated wires is called a *counterpoise*. It is used where the earth under the antenna is very dry or of high resistance for other reasons.

The general scheme is indicated in Fig. 49, the power being supplied to the antenna circuit (generally from an oscillating vacuum tube) at the posts marked "to power supply." The meshwork of radial wires constituting the counterpoise is sometimes bonded together by many interconnecting wires.

For transmitting very short waves the antenna at the broadcasting station may consist of a single vertical copper tube, perhaps 50 feet high. It is supported by insulators on a wooden pole.

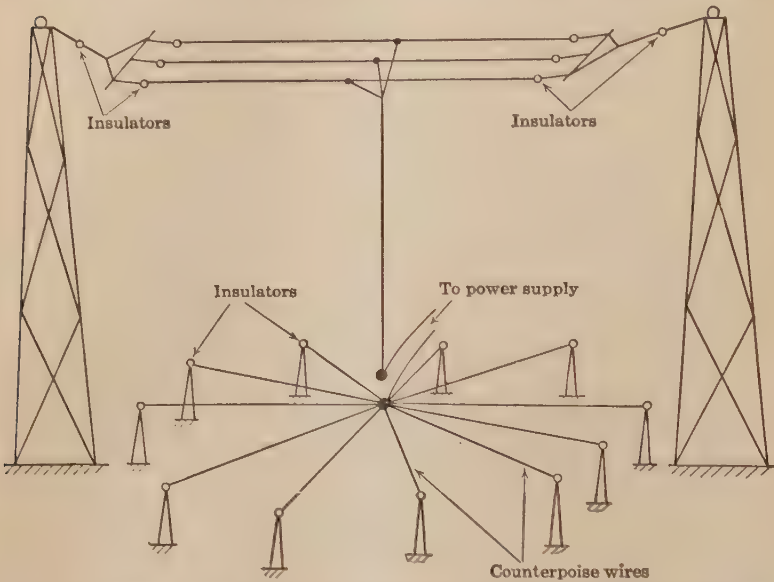

FIG. 49.—Frequently a large transmitting antenna uses a counterpoise, instead of an earth connection.

There is a break in the tube at its center, a coil of a few turns being connected across the break. Power is generally supplied by coupling the coil to one in the high-frequency oscillating circuit of the vacuum tube power supply.

A receiving antenna may be of almost any form and size, within reason. If the radio set has two or more stages of radio frequency amplification and it is not more than fifty miles or so from the broadcasting station a small single wire antenna, perhaps 10 to 20 feet high, will pick up plenty of energy. If the radio frequency amplification is poor, or the distance from the transmitting station great,

it may be advisable to use as an antenna a single wire having a total length of about 150 feet, with a vertical height as great as possible.

Although an outdoor antenna is generally better than an indoor one, in a wooden house the indoor antenna will generally prove sufficient. Preferably it should extend the length of the attic for the horizontal part, and it may run down inside the wall to the place where the radio set is used. The water pipe system of the house makes a good ground.

In apartment houses a wire run around the room on top of the picture molding will generally give reasonable signals. A radiator makes a perfectly good ground, as it constitutes part of the water system.

Frequently a small loop of wire, perhaps fifteen turns 2 feet square, is used as an antenna; but as such a loop antenna picks up but little energy it is necessary to have a receiver with plenty of radio frequency amplification unless the receiver is within 10 miles or less of the transmitting station.

Inside a steel-frame building there may be many dead spots where no radio signal may be found. In such buildings shifting the antenna from one room to another, or even from one side to another of the same room, may bring about unexpectedly great changes in signal strength.

16. How Radio Field Strength is Measured.—The electric and magnetic fields of a radio wave (see Fig. 40, p. 79) travel through space with the velocity of light, 300,000 km. per second. The two fields, traveling with this velocity, are mutually self-supporting. The rapidly moving magnetic field is just able to set up the electric field required to make up the wave.

The strength, or intensity, of a radio wave is measured in terms of its electric field. This field, practically perpendicular to the earth's surface, is measured in *volts per meter*. To make this idea clear let us suppose two large parallel metal plates A and B, Fig. 50, separated by a meter. A battery C, of 8 volts, charges these two plates to 8 volts difference of potential, and there is an electric field between the two plates as indicated in the illustration. The strength of this field would be 8 volts per meter because by going through one meter of the field the difference of potential is 8 volts.

Now suppose the plates are separated 2 meters. We know from

elementary physics that the electric field will be weaker than it was before. We now have to traverse 2 meters of the field before we cover the same difference of potential as before, namely, 8 volts. Hence the field has a strength of 8 volts for 2 meters or 4 volts per meter. If the plates are moved close together say, within $\frac{1}{4}$ meter, then the electric field will be much more intense; this would be a field of 8 volts per $\frac{1}{4}$ meter or 32 *volts per meter.*

Unless the wave from a broadcasting station is measured in the immediate vicinity of the station the electric field is always less than one volt per meter. Within a few miles of a modern broadcasting station the field is measured in *millivolts per meter* and farther away it is measured in *microvolts per meter.*

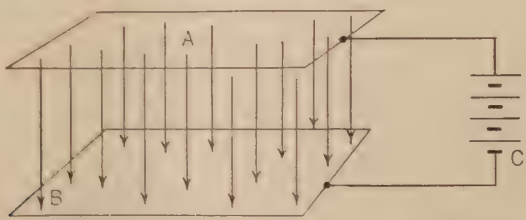

FIG. 50.—A simple arrangement to bring out the meaning of the term "microvolts per meter."

17. Radio Field-Strength Maps.—It is practically impossible to predict what the electric field strength of the radio wave from a given transmitter will be; it is necessary to set up a temporary transmitter at the place the permanent antenna will occupy and to measure, experimentally, the field strength of the small temporary transmitter. The measuring apparatus is mounted in an automobile and the measurements are made at hundreds of points in the surrounding territory, and from these measurements a radio field-strength map for the permanent broadcasting station can be constructed. In such a map the points, surrounding the station, where the field has a certain strength, say 10 millivolts per meter, are connected together. Any listener located at any point on this line, will get a signal of that value in his antenna. If the antenna has a vertical height of 8 meters (about 25 feet) the radio wave will set up in the antenna 8 meters $\times$ 10 millivolts per meter = 0.08 volt. If then the antenna is tuned, so that its reactance is zero, and has a resistance, let us say, of 16 ohms, the radio-frequency current in the antenna will be 0.08 divided by 16 = 0.005 ampere.

Signals measured in millivolts per meter are good signals, that is, the ordinary atmospheric disturbances are of much lower intensity so that the signal comes in without appreciable "static" disturbance. The strength of atmospheric disturbance varies so much at different seasons and times of day, and according to the wave length for which the circuit is tuned, that it is impossible to give even an average figure for its strength. It may vary from practically nothing (a few microvolts per meter) to several hundred microvolts per meter. It is seldom measured in millivolts per meter unless there is an electrical storm in the vicinity.

It is thus evident that if a listener is at such a distance from the broadcast transmitter that the radio map shows the signal strength to be 5 millivolts per meter, a good radio receiving set should give loud signals with inappreciable interference from atmospheric disturbances. If, however, the map shows him to be at a place where the contour lines are marked in a few microvolts per meter then the signal will be unsatisfactory and much of the time the signal will be practically "buried" in the atmospheric noises.

Fig. 51 shows a radio contour map of New York City; the contour lines are marked on an air plane photograph of the city. The broadcast transmitter which was used to send out the signal was located in the top of one of the tall steel-frame buildings in the lower part of the city. It can be seen that there is an extremely rapid falling off in signal strength as the radio waves travel over the district of tall steel buildings. Perhaps a mile away from the transmitter the field strength is 100 millivolts per meter and after traveling only about 3 miles farther it has fallen as low as 1 millivolt per meter. In open country the signal could travel 50 miles before diminishing to such a low value.

It was primarily as the result of measurements such as these that radio engineers came to the conclusion that radio transmitters should never be placed in the center of a large city.

18. Amount of Power Used in Radio.—Naturally the amount of power used to carry on radio communication depends principally upon the distance over which the signal has to travel. Furthermore the amount of atmospheric disturbance present at the receiving station has a most important bearing upon the amount of power required at the transmitter. In some parts of the world a signal strength of only 2 microvolts per meter permits reliable reception whereas in others even 500 microvolts per meter is not sufficiently

FIG. 51.—An actual radio topographic map of New York City and vicinity. The lines of "equal signal strength" have been plotted on an aeroplane map of the city.

intense to eliminate serious interruptions from atmospheric disturbances.

A few examples will show the present practice. For transatlantic telegraph channels low-frequency high-powered stations are used. The frequencies for perhaps a dozen of the largest stations lie between 15 kc. and 25 kc. These stations use from 100 kw. to 500 kw. input to the antenna. They transmit with reasonable reliability over distances from 3000 to 6000 miles. The antenna heights lie between 100 and 300 meters, and the current supplied to the antenna from 200 to 600 amperes.

These high-powered low-frequency stations are carrying on experiments on the relative effectiveness of their normal wave and some very short waves. For example, it seems that to send signals with any degree of reliability half way around the world these long wave stations are not suitable; comparatively small powers (5 kw. to 50 kw.) at a frequency of perhaps 20,000 kc. prove to be much more reliable, and these short-wave channels are now being actively developed.

For broadcasting purposes the amount of power and frequency of the transmitter are controlled by governmental agencies. The broadcasting frequencies lie between 500 and 1500 kc. and the amount of power supplied to the transmitting antenna must not exceed a few kilowatts, except for experimental purposes.

Although it is possible to hear the signal of such a broadcast station as far as 1000 miles or more, on a winter night, the reliable range of such a station for summer as well as winter, day time as well as night, is not more than about 100 miles.

A given amount of power on any wave length will furnish *reliable telegraph communication* several times as far as that over which *distinct telephone communication* is possible, for reasons to be taken up later in the text.

Although the division between good and poor radio reception is necessarily indefinite, engineers have agreed that with ordinary broadcasting receivers a 5-kw. station gives good transmission up to about 100 miles.

A classification, necessarily somewhat arbitrary, has been made by government experts as shown in table on page 98.

By interference range is meant the distance up to which the carrier wave of the station may produce a disagreeable beat note with another station on nearly the same frequency.

Rating of Station, watts	Very Good Service, miles	Good Service, miles	Poor Service, miles	Interference Range, miles
50	2	10	100	600
500	6	30	300	1800
5,000	20	100	1000	6000
50,000	60	300	2000	

The above station ratings are rather pessimistic; on these ratings most of the radio listeners in the United States today have very poor service and most of them must be considered as having none at all! This we know is not so.

As an example, listeners on the channel of one of the 5000-watt stations were satisfied with the reception they were getting even as far as 800 miles from the station. The field strength of this distance from the station, at night, had an average value of 5 microvolts per meter, and varied from 0.1 microvolt per meter to 16 microvolts per meter.

Listeners as far as 100 miles from a 5000-watt station generally have a field strength less than 1000 microvolts per meter. As these listeners are generally well satisfied we must assume that for the average listener, under average conditions of interference, a field strength of 1 millivolt per meter gives reasonably satisfactory service.

In the tabulated results given above it is evident, from inspection, that "very good service" requires above 10 millivolts per meter field strength; few listeners today have a field strength as high as this.

CHAPTER IV

THE VACUUM TUBE AND ITS USES

1. Evaporation of Electrons from Metals.—The whole art of radio communication today depends upon the vacuum tube, and this device depends upon the possibility of evaporating electrons from metals. In the first part of this text there was given an elementary explanation of the constitution of metals, molecules and electrons moving back and forth at high velocities continually colliding with each other.

As the metal is heated the haphazard motions of the molecules and electrons rapidly increase; by the time a metal is raised to a red heat the average speed of the electrons, as they get bumped back and forth by the more massive molecules, has increased to about 300 *miles a second.* When the speed increases to about 600 miles per second the electron is able to break away from the metal; it jumps right through the surface of the metal and exists outside of the metal, as pure electricity. This electron which has *broken through the metal surface,* that is, *evaporated,* is just the same no matter what the metal may be. The electron has none of the characteristics of the metal from which it came.

If there is air surrounding the metal this phenomenon of electron evaporation cannot be brought about. Tungsten, for example, if heated in air to a temperature sufficiently high to produce electron evaporation, at once oxidizes. Furthermore even if electron evaporation could take place from a metal surrounded by air, the electrons would at once go back into the metal. The air molecules, being so much heavier than the electrons, would impede the motion of the free electron so much that it would at once bound back into the metal from where it came.

A pure tungsten filament must be raised to a dazzling white heat before appreciable electron evaporation occurs. Attempts to find other surfaces from which electrons freely evaporate at lower temperatures have been so successful that pure tungsten is practically never used today.

By using a tungsten filament which has been impregnated with thorium, a high electron emission is obtained at a bright-red heat. Examination of this tungsten-thorium filament shows that a very thin layer of thorium forms over the tungsten, a layer only one molecule thick, and that the electron evaporation thus takes place from thorium, and not from tungsten. Such **thoriated-tungsten** filaments are much more efficient than pure tungsten from the standpoint of power consumption; to evaporate sufficient electrons to give a current of 0.5 ampere requires a filament power of 15 watts with thoriated tungsten, and about 60 watts with pure tungsten.

The thoriated-tungsten filament must be treated with more care than a pure-tungsten filament; if the proper operating temperature is appreciably exceeded the thin layer of thorium is evaporated and the emission drops to practically zero. By suitable treatment (described in the manufacturer's catalogue) called **reactivation** the spoiled filament may sometimes be restored to full efficiency.

Even more efficient than the thoriated filament is the **oxide-coated filament.** A thin nickel or alloy ribbon is coated with a thin layer of certain barium and strontium oxides and even at a dull-red heat a copious emission of electrons takes place. For a given electron emission an oxide-coated filament requires only one half as much power, for heating, as is required for a thoriated filament giving the same emission.

A properly manufactured oxide filament has a life of many thousand hours if treated properly. With too high a temperature the oxide coating chips off and the filament is spoiled. It cannot be reactivated in the same manner as a spoiled thoriated filament.

In Fig. 52 are shown the comparative merits of tungsten and oxide-coated filaments, as electron emitters. A filament of 1 sq. cm. surface has been assumed and on the plot are given the temperatures and amount of electron emission for the different amounts of power supplied to the filament. Thus the tungsten filament, if supplied with 60 watts for heating, will rise to a temperature of 2370° (absolute centigrade) and will emit about 0.2 ampere. Its life will be about 700 hours. An oxide-coated filament supplied with 8 watts of power to heat the filament will rise to 1240° and will emit 0.2 ampere, the same as the tungsten filament using nearly eight times as much power. The life of the oxide-coated filament

at this temperature, if well manufactured, will be 3000 hours. The thoriated filament lies, on this chart, between the tungsten and the oxide-coated filament, somewhat nearer the latter.

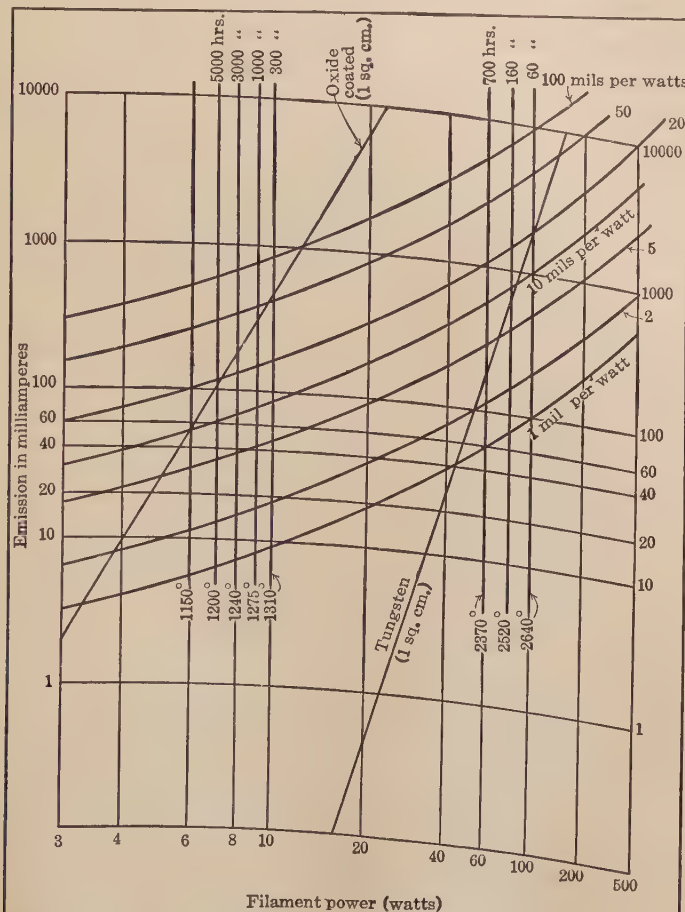

FIG. 52.—A chart to show how the emission current of a hot surface varies with temperatures, and type of filament. A filament having 1 sq. cm. of surface gives an emission current shown by the straight lines, slanting toward the right.

2. Vacuum and How Obtained.—For two reasons at least the filament that emits electrons must be in a highly evacuated vessel. With appreciable air surrounding the filament this would spoil at

its operating temperature and furthermore unless the filament is in a vacuum the electrons emitted from the filament could not be effectively used, as will be explained later.

During the process of manufacture, the filament and other metallic parts which are to be used in the tube are assembled in their proper relation, generally by glass fastenings. These are then sealed into a suitable bulb and this is connected by glass tubing to a vacuum pump. The latter is started and after most of the air has been pumped out the filament and other metallic parts, as well as the glass bulb itself, are heated as hot as feasible. This drives much gas out of these parts and the pump being in operation takes off all this gas. When the pressure has been reduced to about 10^{-4} mm. of mercury pressure the tube may be sealed off from the pump. This pressure means that only about $\frac{1}{10,000,000}$ of the air originally in the tube is left there.

The evacuating is generally done nowadays by the mercury-vapor pump. A stream of mercury vapor, boiled off from a pool of mercury, shoots at high velocity through a glass tube into the side of which is sealed the glass tube leading to the vacuum tube to be exhausted. The mercury-vapor stream acts just like an ejector, dragging along with itself the gas from the vessel to be evacuated.

The mercury-vapor pump is generally used in series with a pump of the ordinary kind, rotating or reciprocating. With this combination the air is taken out in a few minutes. Atmospheric pressure will raise a mercury column 76 cm.; in a short time these pumps will lower the pressure to about *one micron* (0.001 mm.) of mercury and if suitable precautions are taken, liquid air traps used, etc., the pressure may be reduced to perhaps 10^{-7} mm. Instead of taking time to do this, however, another method of final evacuation is used.

3. Getter.—To complete the evacuation process, after the tube has been sealed off from the high-vacuum pumps, one of the easily volatilized metals is used. Magnesium, sodium, caesium and such metals are used. A small piece of the metal is fastened to the seal-in wires or on an extra disc-shaped piece of metal built into the tube structure for that purpose. The sealed tube is placed inside a solenoid through which high-frequency current is flowing; all the metal parts inside the tube have currents induced in them and

so they are heated and the small bit of magnesium or other volatile metal is vaporized and condenses on the inside wall of the bulb. This gives the well-known silvery coating seen inside the ordinary vacuum tube. Generally the metal does not condense evenly over the inside wall; there will generally be parts of the bulb with an opaque coating while other parts may have almost no deposited metal.

This freshly condensed metal acts toward the residual gas in the tube as a sponge acts towards water; it " soaks up " the remaining gas, or " gets " it with great rapidity. This last step in the evacuation process is called the " clean-up." The life of a vacuum tube depends primarily upon the efficiency of the clean-up process.

4. Effect of Poor Vacuum.—There are two bad characteristics to a poorly evacuated tube; the filament may become " poisoned " and thus cease to emit electrons as it should, and even before this occurs the action of the tube is erratic. It may in fact cease to function at all.

The thoriated filament has a layer of thorium only one molecule thick over the tungsten; it is this molecular layer of thorium which permits the copious emission of electrons at comparatively low temperature. Now if there is appreciable gas left in the tube after evacuation the result is as follows:

The electrons which are emitted from the filament are pulled over the plate, one of the cold electrodes of the ordinary vacuum tube. They travel with very high velocity, several thousand miles per second. Some of these high-speed electrons collide with gas atoms and break free one or more electrons; that is, they *ionize* the gas. The freed electron travels along with the original one and the positively charged gas atoms move in the opposite direction, that is, toward the filament. When they reach the filament they are moving with high speed and the energy of the collision will disrupt to some extent the atom-deep layer of thorium. If this bombardment by positive gas atoms takes place to an appreciable extent the thoriated filament becomes practically useless as a source of electrons.

In addition to this effect of filament damage the behavior of a tube with ionized gas is very erratic. If it is being used as a detector it may stop functioning completely; if it is being used as an amplifier its amplifying power may be much reduced and it is the source of much " noise " in the loud speaker. In case the

ionization is more than the small amount we have supposed, a light bluish glow appears in the tube; when this takes place the amplifier is dead, for reasons brought out later in this chapter.

5. What is a Good Vacuum.—The steam engineer thinks he has a "good vacuum" when his condenser shows a pressure of 10 mm. of mercury, the normal atmospheric pressure being 760 mm. In the ordinary process of evacuation used for radio tubes, pressures as low perhaps as 0.0001 mm. of mercury are reached. After the getter has functioned the pressure may go as low as 10^{-5}, or even possibly 10^{-6}, mm. of mercury.

With the best refinements available in a good laboratory, using charcoal and liquid air as assistants to the pumps, it is possible to get a vacuum as low as 10^{-8} mm. of mercury. Now even with this degree of vacuum there are still approximately 10^8 molecules per cubic centimeter of our supposedly perfect vacuum. This means that the gas molecules are on the average only about 0.001 cm. apart!

At atmospheric presssure there are enough gas molecules per cubic centimeter to make the average distance between them about 0.000001 cm.; by our most perfect evacuating processes we are able to thin them out to increase the average distance of separation one thousand times. In the average vacuum tube the gas molecules are only about 0.0001 cm. apart. It is evident, then, that "vacuum" is only a comparative term.

6. The Two-electrode Tube or Diode.—If a hot filament is in the same evacuated vessel as another electrode, such as a small plate of suitable metal, the combination forms an electric valve, that is, current will flow through the device in one direction but not in the other. Electrons are evaporated from the hot filament, but not from the cold plate. If therefore the plate is made positive with respect to the filament the electrons, evaporating from the filament, cross the vacuous space to the plate, enter it, and then flow around the external circuit back to the filament. If however the plate is made negative with respect to the filament, there will be no electron flow because there are no electrons free to leave the plate to cross the vacuous space to the filament. The only free electrons, available to flow across the space between plate and filament, are already at the surface of the filament.

Such a **two-electrode tube,** or **diode,** will then pass current when the plate is made positive with respect to the filament, and

will not pass current when the plate is negative with respect to the filament. In radio reception some rectifying device is necessary to make the high-frequency signals audible in the telephones. Fleming was the first to see that the two-electrode vacuum tube was suitable for such use and to use it so; the device was called a **Fleming valve.**

Fig. 53 shows the Fleming valve as actually used on early receiving sets; on either side of the small hair-pin filament a nickel plate was placed, about 2 mm. away and the electrons evaporating from

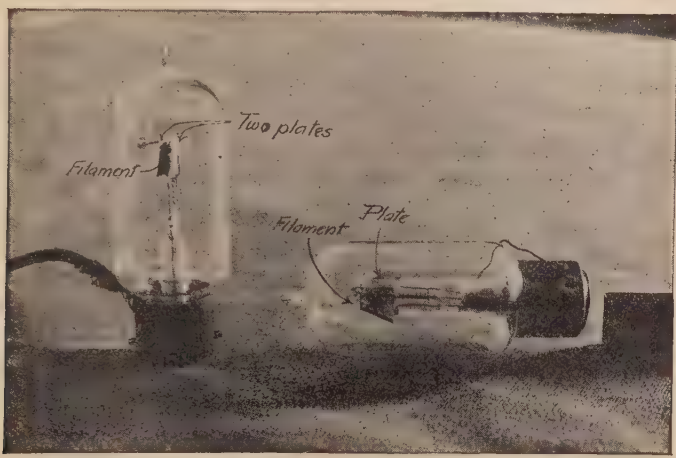

FIG. 53.—Two Fleming valves, used on early types of receivers.

the filament crossed this space to either plate when this was made a few volts (about 20) positive with respect to the filament.

7. Characteristic Curves of Two-electrode Tube.—In Fig. 54 are shown three of the characteristic curves of a small diode; for a negative plate the current was so nearly zero that it could not be read on the ammeter being used. The vacuum in this tube was reasonably high (much better than was used in the actual Fleming valves) and no appreciable current flowed with a negative plate, even when this was made as great as 300 volts below the filament potential.

The three curves of Fig. 54 are for different filament currents. For the low filament temperature of curve 1, 30 volts (positive) on the plate was sufficient to attract to the plates *all of the electrons evaporated from the filament;* it is seen that for voltages greater than

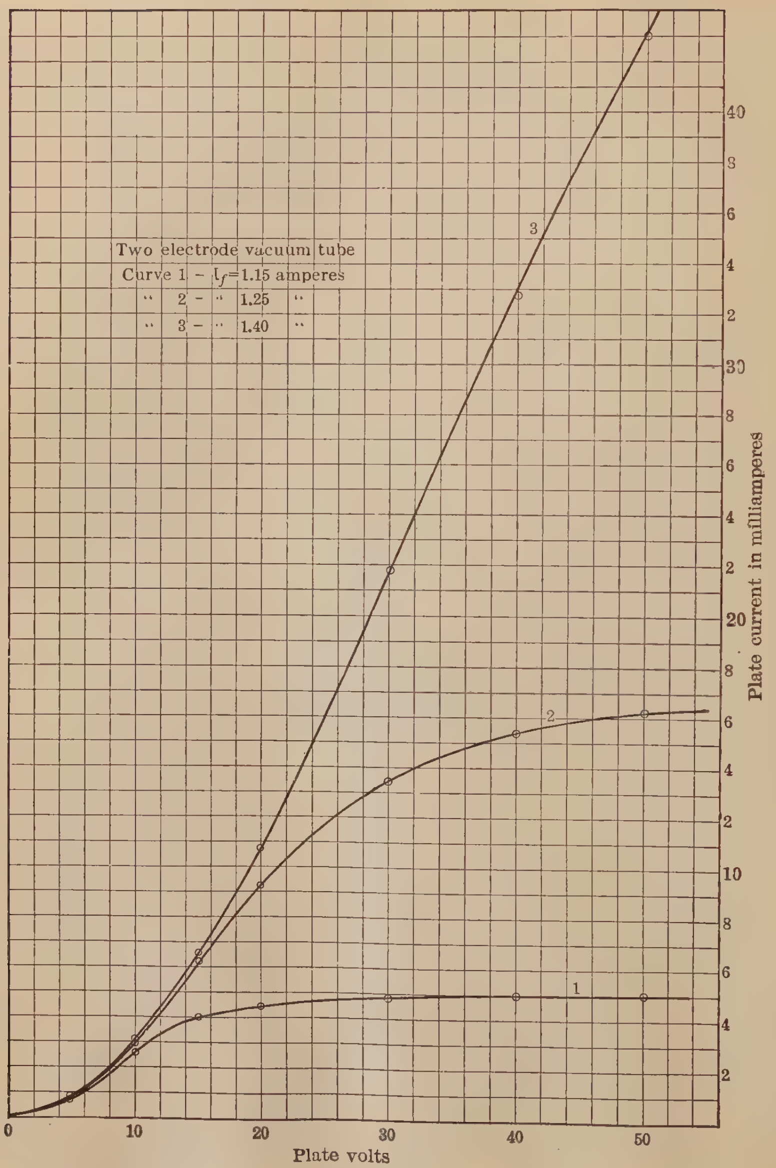

FIG. 54.—Curves of plate current vs. plate voltage, of a diode, or two-electrode tubes.

30 the plate current did not increase at all. It would not have increased even if the voltage had been raised to several hundred.

For curve 2 the filament was held at a higher temperature, so more electrons evaporated. Even 50 volts on the plate was not quite sufficient to pull away from the filament all the electrons evaporating, but about 60 volts would have done so. For curve 3 there was a much more copious supply of electrons (due to the higher filament temperature) and it would have required 100 volts or more on the plate to pull across all the electrons.

It will be noticed that for all three curves, at the lower voltages, the plate current increases much more rapidly than the voltage. The curve is nearly a parabola, that is, the equation between voltage and current is

$$I_p = kE_p^2. \qquad (47)$$

8. Direction of Current in a Diode.—It is to be noticed that the conventional direction of current flow is from the positive pole

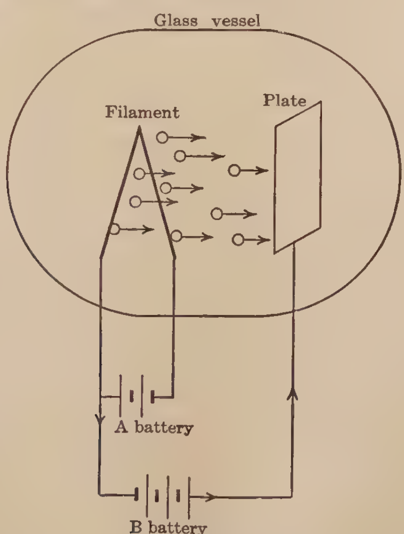

FIG. 55.—Showing the direction of electron flow is actually opposite to the conventional direction of current flow as indicated by the arrowheads in the plate circuit.

of a battery, through the outside circuit, and so back to the negative pole. In Fig. 55 is shown a diode with its two circuits; the A battery (of about 6 volts) supplies power to the **filament circuit** and

the B battery, of about 25 volts, serves to hold the plate positive with respect to the filament. The path through the B battery then to the plate, then across the vacuous space to the filament and so back to the negative terminal of the B battery is called the **plate circuit.**

According to convention we must indicate the plate circuit current as flowing in the direction of the arrowhead; but we notice the electrons, inside the tube, are flowing in the plate circuit in a direction *opposite* to the arrowhead. And of course the plate circuit current, throughout the entire circuit, consists of electron flow in the direction opposite to the arrowhead. We adhere to the conventional direction of current, but many times, in analyzing the actions inside the vacuum tube, it must be remembered that there is nothing flowing from plate to filament (if there is no ionized gas in the tube) but that the electrons are flowing in the opposite direction, i.e., from the filament to the plate.

9. Uses of Two-electrode Tube.—Originally the two-electrode tube was used as a rectifier, or detector, in a receiving circuit; this was the Fleming valve. It is never used as a detector nowadays; the three-electrode tube has superseded it, being more efficient.

But the diode is used a great deal in modern radio outfits, both transmitters and receivers, to rectify an alternating current power supply, to get a continuous current power supply for the plate circuits of the three-electrode vacuum tubes. For receiving sets the diodes are made to rectify alternating power supplies as high as 500 to 1000 volts (alternating current) and to deliver a rectified current of a few tenths of an ampere. In the transmitting circuits the diodes carry amperes of plate current, and rectify alternating-current power supplies as high as 20,000 volts. Sometimes two filaments and two separate plates are mounted in the same tube; this construction permits the rectification of both alternations of the alternating wave; they are sometimes called *full-wave rectifiers.*

10. The Three-electrode Tube, Audion, or Triode.—Deforest discovered that if he put a mesh, or grid-like metallic screen, between the plate and filament of the diode the tube became a much more sensitive detector of radio signals, and also that it might be used as an amplifier of the radio signals. He named this three-electrode tube the **audion,** but it is more properly styled today the **triode.**

The grid in Deforest's early tubes was merely a zig-zag piece of wire interposed between the hair-pin filament and the flat plate. In the modern triode the plate is generally a cylinder, of elliptical cross-section, and the grid is an elliptical shaped spiral of fine wire closely spaced. The potential of the grid controls the plate current more closely as the grid is made of finer mesh, and is made to more completely surround the hot filament. Figure 56 illustrates this idea; two tubes are shown in cross-section, one having a fine grid and one having a coarse grid. In the structure of (a) the electrons trying to get from filament, F, to plate, P, are obliged to pass

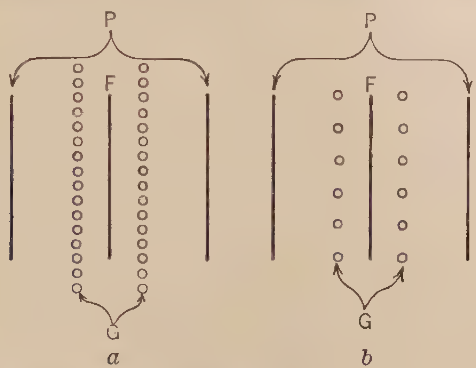

FIG. 56.—Two types of grid construction; the grid of diagram a is much more effective in controlling the plate current than that of b.

very close to the wires of the grid and so are affected strongly by the potential of the grid. In the construction of (b) the electrons can get to the plate more readily as they do not have to pass so close to the grid wires, if they go through the grid, and furthermore some of them may flow from filament to plate by going around the ends of the grid.

11. Equation for Plate Circuit of the Triode.—From what has been said in the foregoing section it is evident that if the plate voltage is held constant, at some positive value, more or less electrons will flow from filament to plate *depending upon the potential of the grid.* If the grid goes positive (with respect to the filament) the plate current is increased and the grid itself takes a small current; if the grid goes negative the grid draws no current at all, and the plate current is diminished.

It has become customary in triode analysis to *refer the grid*

potential to that of the negative end of the filament, if continuous current is used to heat the filament; if alternating current is used to heat the filament the grid potential is referred to that of the center point of the filament.

The plate current of a triode may be changed in two ways: the potential of the plate may be changed, or the potential of the grid may be changed. Expressing this relation in the form of an equation,

$$I_p = K(E_p + \mu E_g)^x. \quad . \quad . \quad . \quad . \quad . \quad (48)$$

Although tubes differ among themselves in their behavior, and the action of a tube with high plate voltage may be somewhat different than when the plate voltage is low, eq. 48 gives a reasonably accurate relation for all ordinary tubes. The factor K is fixed by the general makeup of the tube, size of filament and plate, separation of filament and plate, etc. The factor μ has to be put in the equation because the plate current is generally affected to a different degree if the grid potential is altered, say one volt, than if the plate voltage is altered one volt. The exponent, x, is about 2 for the ordinary triode.

12. Amplification Constant of Triode.—If we test the characteristics of ordinary commercial triodes it will be found that the grid potential is much more effective in controlling plate current than is the plate potential itself. Thus if with a given tube we raise the plate potential by one volt the plate current may increase by 5 milliamperes, the grid potential remaining fixed. If now we keep the plate potential fixed at its original value and raise the grid potential, sufficiently to increase the plate current again, 5 milliamperes, it will be found that the grid potential has been raised, say, only 0.2 volt. This means that 0.2 volt on the grid is worth 1.0 volt on the plate, in so far as plate current is concerned. That is, the grid is 5 times as effective as the plate, in controlling the plate current. This *relative effectiveness* of the grid potential and plate potential in controlling plate current is called the *amplification constant* of the triode. The factor μ, of eq. 48, is the amplification constant.

In the old Deforest audions one volt on the grid had the same effect on plate current as about 2 volts on the plate; the factor μ was therefore 2. In the ordinary amplifying tube used in radio receivers today one volt on the grid has the same effect on plate

current as 8 volts on the plate; the amplification constant is therefore 8.

The amplification factor of a triode with the construction of (*a*) in Fig. 56 would be about 40, whereas that shown in (*b*) of the same figure would be about 5. By using wires a few thousandths

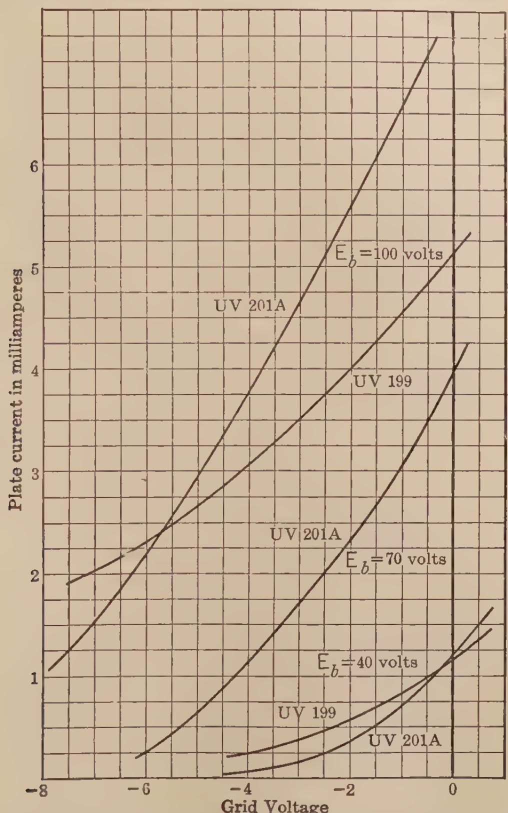

FIG. 57.—Characteristic curves (plate current vs. grid voltage) of two of the more common types of triode.

of an inch in diameter for the grid, and spacing them about 100 to the inch it is possible to get an amplification factor of as much as 200. This seems to be a practical limit for the amplification constant, and even this is much greater than is generally useful in radio circuits.

13. Action of the Grid. Grid Current.—In Fig. 57 are shown some characteristic curves for two types of triodes that have had

almost universal use in receiving sets. The type UV 199 tube is one which uses only 0.06 ampere at 3 volts, to heat its thoriated filament. The UV 201A tube is the standard tube for the average radio receiver, it uses 0.25 ampere at 5 volts to heat its thoriated filament and it is generally used as an amplifier with from 90 to 135 volts in the plate circuit.

The curves of Fig. 57 show the relation between plate current and grid potential; only negative grid potentials are shown because amplifying tubes are never used with a positive grid, for reasons taken up later.

For the 201A tube three curves are given, showing how the grid potential controls the plate current for three different plate voltages. They have the same general shape, but evidently show that the higher the plate voltage, for a given grid potential, the higher is the plate current. Now it can be seen that we have the *same plate current, for the three different plate voltages, provided the grid potential has a proper value for each plate voltage.* For example, the tube carries one milliampere in its plate circuit for the combinations

$$(E_b = 100, E_g = -8), (E_b = 70, E_g = -4.2)$$

or

$$E_b = 40, E_g = -0.4).$$

Looking at the first two pairs of values it is evident that diminishing the plate voltage by 30 volts can be neutralized, in so far as plate current is concerned, if the grid voltage is raised 3.8 volts. The grid is evidently 3.8 volts higher potential at -4.2 than at -8.0 volts. So we may say 3.8 volts in the grid are as effective as 30 volts on the plate; this makes the amplification constant equal to $30 \div 3.8 = 7.9$. In the same way, dropping the plate voltage from 70 to 40 volts may be compensated for by raising the grid potential from -4.2 volts to -0.4 volt. Again 3.8 volts on the grid are as effective as 30 volts on the plate.

When the grid of such a tube as the 201A type is negative it draws so small a current that an ordinary galvanometer will not measure it; if, however, the grid is allowed to go positive (with respect to the negative end of the filament) it draws a current which increases rapidly as the grid goes more positive. Fig. 58 shows this effect; on the curve sheet are shown both plate current and grid current, the grid current being plotted to a scale ten times as large as the plate current. Thus at a grid voltage of zero the plate cur-

rent is 410 microamperes and grid current is zero; at one volt positive on the grid the plate current is 815 microamperes and the grid current is 14 microamperes. The grid current increases practically as the square of the grid potential. For all negative grid potentials the grid current was so small that it could not be measured with ordinary meters.

If the grid of a triode *does* draw current when the grid is negative

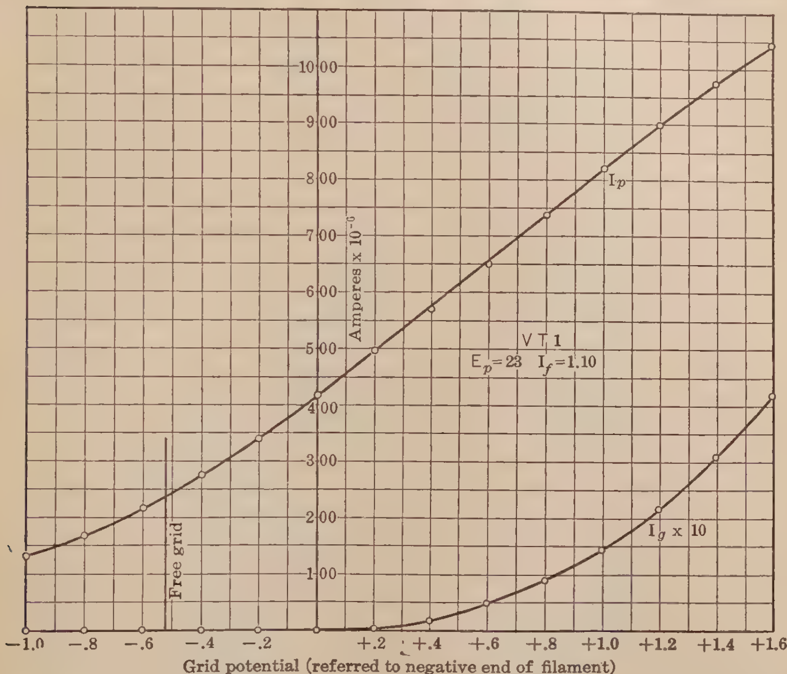

FIG. 58.—Forms of plate current and grid current of a telephone repeater tube.

there must be ionized gas in the tube. In fact, the amount of grid current under such conditions is used as an indicator of the amount of gas left in the tube after evacuation. Figure 59 shows this effect for a large power tube. It may be seen that there was a definite, small amount of negative grid current; the plate current of such a large tube would be about 0.5 ampere and the curve shows the grid current in the negative direction to be only one or two microamperes. We have the rule, then, that with a negative grid the well-evacuated triode draws a current so small as to be ordinarily negligible.

14. Space Charge.—As normally used the plates of a triode draw over only a fraction (never more than half) of the electrons being evaporated from the filament. Many of the electrons which evaporate fall back again into the filament. The reason that the plate cannot ordinarily pull over all the electrons that evaporate is generally explained in terms of **space charge.** The evaporated electrons are crowded together in the space immediately around the filament, those closest to the filament will evidently be pushed back into the filament by the repelling force of all the other electrons between them and the plate. Figure 60 is an attempt to picture this. Many of the electrons experience sufficient attractive force from the plate to be pulled over, but one near the filament, such as electron (a) of Fig. 60, experiences so strong a repelling force from the electrons between it and the plate that it is pushed back into the filament. If there were no such action all the electrons which evaporate would pass across to the plate even if this was at a very low positive potential.

The electrons in the space between the filament and plate constitute the *space charge*

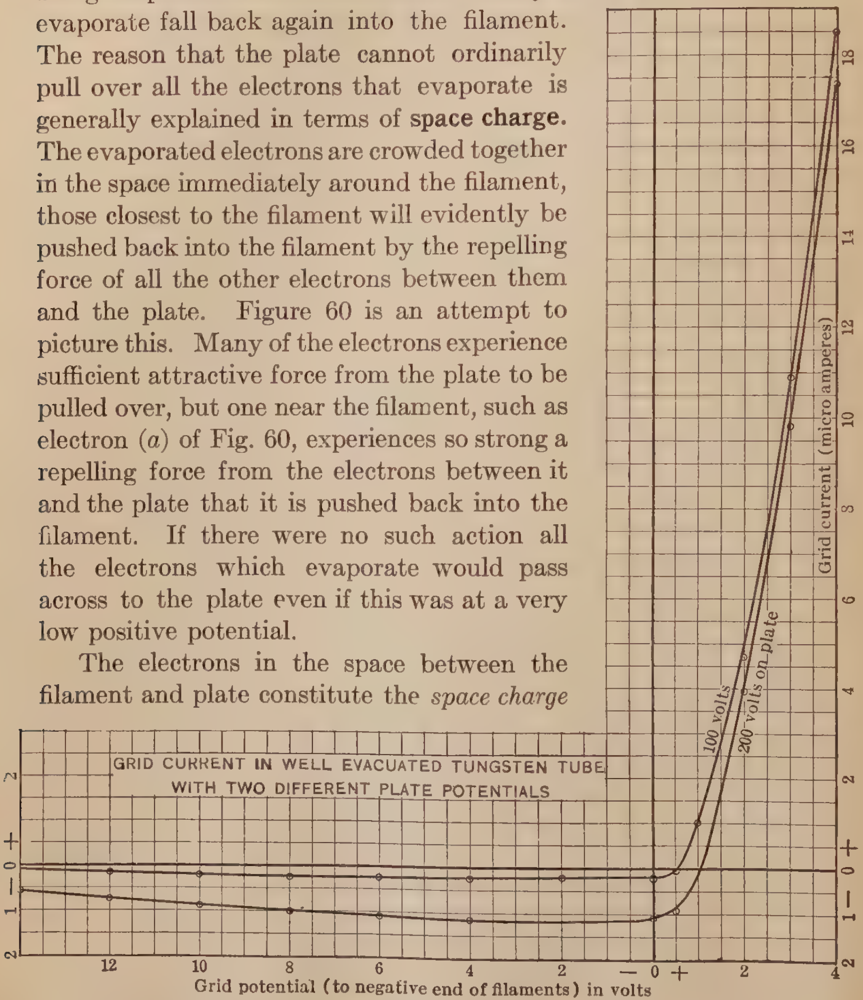

FIG. 59.—Grid current curves for a highly evacuated 250-watt power triode.

of the triode; the reason electron (a) of Fig. 60 does not go across to the plate is because the space charge pushes it back to the filament. If the plate potential is increased it will overcome more of the space charge effect and so more of the evaporated electrons will

be pulled across, that is, the plate current is increased. In the triode as normally used many more electrons are evaporated than go across to the plate; the *plate current is limited by the space charge.*

Now the grid is placed right in the space charge; if it is held at a negative potential it will evidently assist the space charge (which is made up of negative electrons) in limiting the plate current. But if the grid is charged positively its positive charge will neutralize to some extent the space charge and so the plate current increases. This explains the control of the plate current by the grid potential, *in terms of the space charge.*

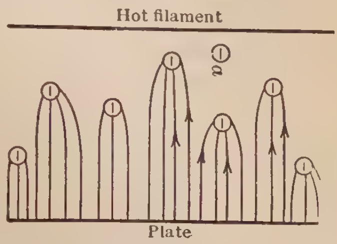

FIG. 60.—Diagram to illustrate *space charge.*

15. Equivalent Circuit of the Triode.—When used as an amplifier or detector the signal is impressed between the grid and filament; these are called the **input terminals** of the triode. This is indicated in Fig. 61, diagram *a*. The alternating signal voltage, e_g, acting between the grid and filament, makes the plate current increase and decrease, resulting in a fluctuating plate current.

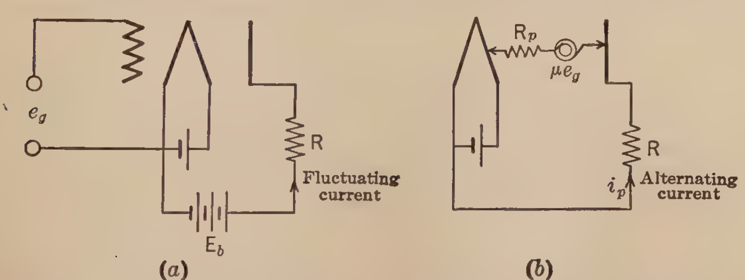

FIG. 61.—The triode of diagram *a* is electrically equivalent to the diode of diagram *b*.

The triode can be replaced by a diode (diagram (*b*) of Fig. 61) in which an alternator is supposed to be in the plate circuit, between plate and filament, the voltage generated by this alternator being of the same frequency as e_g (of (*a*)) but greater in magnitude than e_g, by an amount depending upon the triode's amplification constant, μ. That is, in the plate circuit we introduce the voltage $\mu\, e_g$. This voltage acts in the plate circuit through two resistances, the

resistance R_p between the plate and filament of the triode, and the resistance R which is in the external part of the plate circuit. The triode then reduces to the simple circuit of Fig. 62, two resistances in series, R and R_p, and two voltages in series, the battery E_b and the alternator $\mu\, e_g$. The steady part of the plate current is given by E_b and the fluctuating part by $\mu\, e_g$.

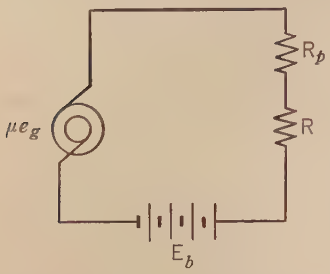

FIG. 62.—This is the circuit which is electrically the equivalent of the plate circuit of a triode.

16. Plate-circuit Resistance. Variation with Voltage.—The resistance of the plate circuit of the triode is given by the relation between the current flowing to the plate from the filament, and the voltage between the plate and the filament. The grid is supposed to be at zero potential, that is, connected to the negative end of the filament. If the plate current is 2 milliamperes when the plate voltage is 40 the plate circuit resistance is $40 \div 0.002 = 20{,}000$ ohms. This is the resistance of the plate circuit for direct, or continuous, current. It is designated by R_{op}.

If the resistance is measured for different values of plate voltage it will be found that the circuit does not act like an ordinary resistance. The higher the voltage, the lower is the resistance; in fact, the resistance varies inversely with the plate voltage as shown in Fig. 63. This tube was designed for a minimum plate voltage of 22, so its normal resistance is 10,000 ohms or less.

The resistance of the plate circuit for *changes in plate current* is much different than the resistance analyzed above. If we indicate small change in plate voltage by ΔE_p and the corresponding change in plate current as ΔI_p and the corresponding resistance R_p we have

$$R_p = \frac{\Delta E_p}{\Delta I_p}. \qquad \qquad (49)$$

This alternating-current resistance is only about one-half as much as the resistance R_{op}; it varies in the same way with the magnitude of the plate voltage.

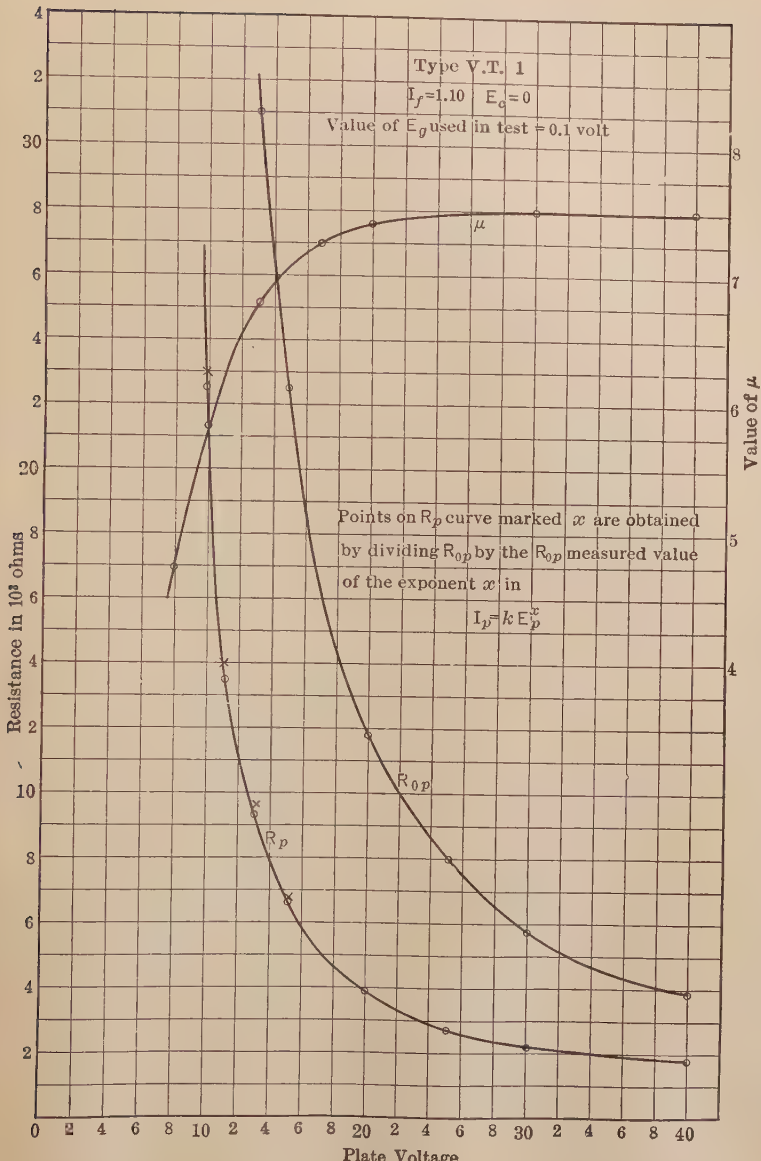

FIG. 63.—Curves of plate resistance and amplification factor of a triode, showing their variation with plate voltage.

The plate current of a tube varies with the plate voltage to the x power, as given in Eq. 48, and it can be shown that

$$R_p = \frac{R_{op}}{x}. \qquad (50)$$

Now for ordinary tubes the exponent x is 2, from which it follows that we have

$$R_p = R_{op}/2. \qquad (51)$$

In Fig. 63 there is shown the curve of R_p for comparison with the R_{op} curve of the same tube. This curve of R_p was measured experimentally at the points shown by the small circles; the points on the curve marked with a cross were obtained from the R_{op} curve by using eq. 50.

There is also shown in Fig. 63 the experimentally measured value of μ, the amplification constant. Although this decreases with the lowest voltages shown on the curve, it is constant for voltages at which the tube was intended to be used. It is always assumed in vacuum-tube theory that μ is a constant and this curve shows that, at plate voltages above 22, for which the tube was designed, such is the fact. For the very low plate voltage μ may change, sometimes increasing and sometimes decreasing, as it does in Fig. 63.

17. Grid Circuit Resistance. Variations with Grid Bias.—In Fig. 64 is shown a simple receiving circuit using a triode for amplifier and detector. It may be seen that the grid-filament circuit of the tube is in parallel with the tuning condenser. The resistance of this circuit is then extremely important; if it is not very high it will be practically impossible to tune the receiving circuit because a low resistance across the tuning condenser will spoil the tuning qualities of the circuit. A resistance shunted across a condenser may be changed into an equivalent series resistance by the use of eq. 38, p. 68. The circuit acts, in so far as tuning is concerned, as though this equivalent series

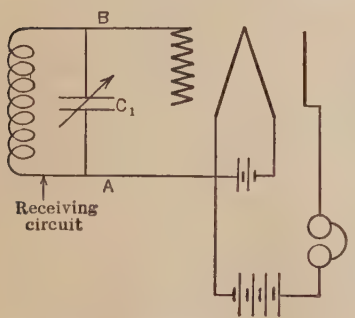

Fig. 64.—Connection of triode, showing signal put on the grid, or input circuit, and detected in the plate circuit.

resistance were actually in series with the coil or condenser of the tuned circuit.

Let us suppose the coil of Fig. 64 has an inductance of 200 microhenrys and that the tuning condenser has a maximum capacity of $400\mu\mu f$ and a minimum capacity which, added to the stray capacity of the circuit, makes the minimum circuit capacity $45\mu\mu f$.

At maximum capacity the circuit frequency is obtained from the relation of eq. 27, p. 48, $f = \dfrac{1}{2\pi\sqrt{LC}}$, and this gives 560 kc. At this frequency the coil resistance, using the results of Fig. 28, p. 63, might be 3 ohms.

At minimum capacity the resonant frequency is 1670 kc. and at this frequency the coil resistance would be about 22 ohms. These values of resistance give the coil a power factor of about $\frac{1}{2}$ per cent at the lower frequency and 1 per cent at the higher. These are reasonable values for good coils.

Now let us suppose the grid-filament resistance of Fig. 64 is 100,000 ohms. From eq. 38 the equivalent series resistance at the lower frequency, 560 kc., is

$$R_s = \frac{10^{12}}{(2\pi 560{,}000 \times 0.0004)^2 \times 100{,}000} = 5 \text{ ohms.}$$

Therefore the circuit would tune as though its resistance was 3 ohms (coil) plus 5 ohms (condenser) = 8 ohms. That is, the effect of the grid filament resistance has been to increase the resistance to almost three times that of the coil alone. This would make the tuning curve about three times as broad as it should be, that is the selectivity would be only one-third as sharp as it should be.

At the high frequency, 1670 kc., similar calculation gives an equivalent series resistance for the condenser of 43 ohms. As the coil has a resistance of 22 ohms for this frequency the total circuit resistance is 65 ohms and this again is about three times the resistance of the coil. So here also the selectivity of the circuit would be only one-third as good as it should be.

From this one illustration it is seen at once that the resistance between the grid and filament must be kept very high if sharp tuning of the circuit is desired.

If a so-called " biasing " voltage is used in the grid circuit, to maintain the grid at an average potential negative with respect

to the negative end of the filament, the resistance of the input circuit of the triode is much increased. In Fig. 65 there is shown the experimentally determined characteristic of the input circuit of a triode. The values are plotted in terms of **input conductance,** measured in micromhos. A conductance is the reciprocal of a resistance; if a circuit has one micromho of conductance its resistance is one million ohms. If its conductance is 5 micromhos its resistance is 200,000 ohms, etc.

The triode measured in Fig. 65 had 11×10^{-6} mhos (11 micro-

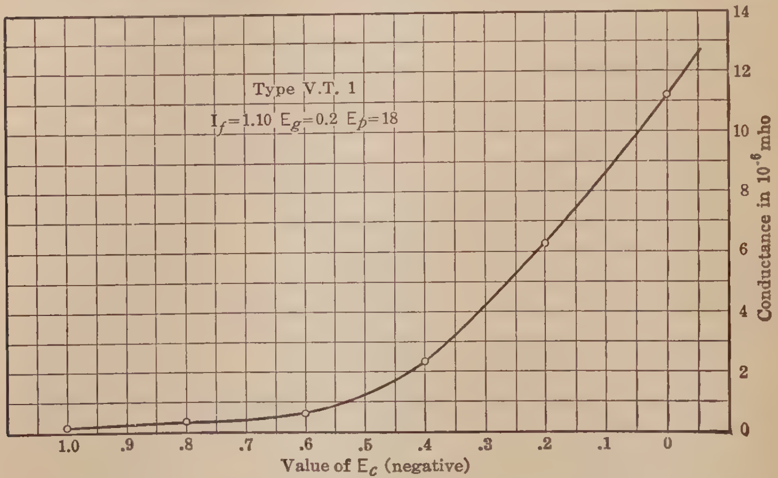

FIG. 65.—The conductance of the input circuit decreases rapidly with increase in negative grid biasing voltage.

mhos) conductance with zero grid potential. This corresponds to 90,000 ohms input circuit resistance, about the same as we used in the foregoing problem. By putting a negative bias of 1 volt on the grid its input conductance is diminished to 0.2 micromho, which means an input resistance of 5 megohms. Assuming such an input resistance in the above problem then, at 560 kc., the equivalent series resistance of the condenser would be 0.1 ohm and at 1670 kc. it would be 0.8 ohm. Both of these values are negligible compared to the coil resistances of 3 ohms and 22 ohms, respectively, so that the input circuit would now have a negligible effect on the tuning of the set. This is one of the factors which accounts for the almost universal use of grid bias in tuned triode amplifiers.

To get the grid bias, a small dry cell may be put in series with the input circuit of the triode or a suitable connection is made to utilize some resistance drop in the filament circuit, or plate circuit, of the triode. In Fig. 66 both of these schemes are indicated; in (*a*) a resistance, R, inserted in the negative side of the filament circuit makes the grid more negative than the most negative part of the filament by an amount equal to the filament current multiplied by the number of ohms in this resistance. In the scheme of (*b*) in Fig. 66, one cell of battery C, serves to maintain the grid 1.5 volts negative with respect to its filament.

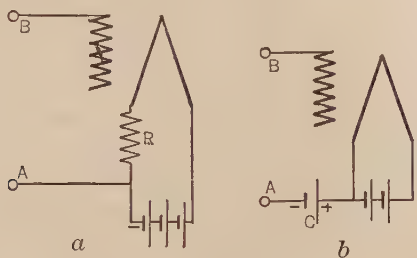

Fig. 66.—Two methods of obtaining a negative grid bias.

18. Mutual Conductance.—In Fig. 61, p 115, we have indicated how the triode may be represented by an equivalent diode; the alternating voltage, e_g, impressed on the grid filament of diagram (*a*) produces in the plate circuit a corresponding alternating current. As there is in addition to this alternating current the steady value of current produced by the B battery the actual plate circuit current is a fluctuating direct current. But in so far as amplification is concerned the steady component of plate current is of no service, so in diagram (*b*) of Fig. 61 this current is omitted and only the alternating component of the actual plate current is shown.

In the analysis of Fig. 61 it was shown that the grid voltage, e_g, is replaceable by an alternating voltage in the plate circuit equal to μe_g. Now if the total resistance in the plate circuit is that inside the tube R_p (that is, the external portion of the plate circuit has a negligible resistance) then it follows that

$$I_p = \frac{\mu E_g}{R_p}, \quad \ldots \ldots \ldots \quad (52)$$

where I_p = alternating current in plate circuit (effective);
E_g = alternating voltage impressed on grid (effective);
R_p = alternating current resistance of plate circuit;

we can write this equation.

$$I_p = E_g \times \frac{\mu}{R_p} = E_g \times g_m. \quad . \quad . \quad . \quad . \quad . \qquad (53)$$

in which g_m is called the **mutual conductance** of the triode. It is not a very well chosen term because the conductance is not a

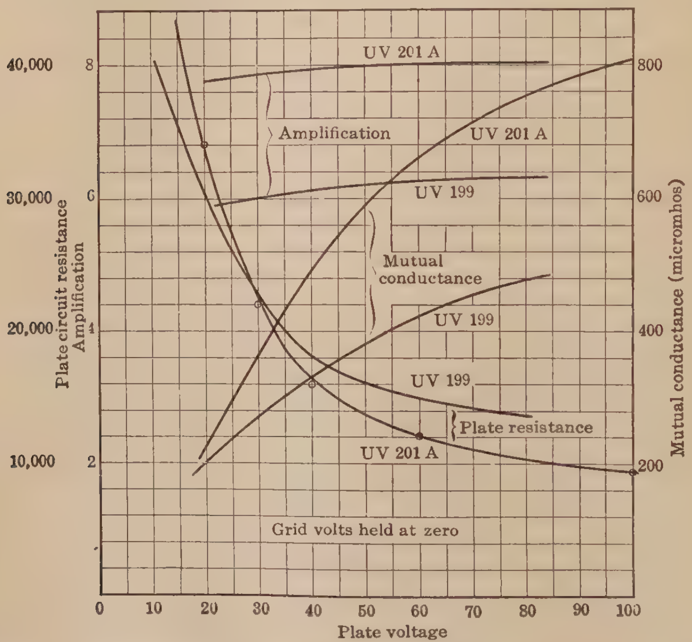

Fig. 67.—Characteristic curves of two of the ordinary types of triodes.

mutual one in the true sense of the word, but it has however come into wide use in the triode literature.

In the average triode used today in radio receivers the mutual conductance is a few hundred micromhos, that is, one volt (alternating) impressed between grid and filament will produce an alternating component in the plate circuit of a few hundred microamperes.

In Fig. 67 are shown characteristics of two of the small triodes

which have had most extensive use in American receiving sets. The amplification of the 201A triode, at 100 volts, in the plate is (from the curve sheet) 8.1; the alternating current resistance of the plate circuit is 9800 ohms. Using then eq. 52, above, to find the alternating plate current when one volt of alternating e.m.f. is impressed on the input circuit

$$I_p = \frac{8.1 \times 1}{9800} = 825 \text{ microamperes.}$$

And from the value of mutual conductance 825 micromhos at a plate voltage of 100, as read from the curve, we have, using eq. 53,

$$I_p = 1 \times 825 \times 10^{-6} = 825 \text{ microamperes.}$$

This is the effective value of the alternating plate current, the maximum value is $825 \times 10^{-6} \times \sqrt{2} = 0.00116$ ampere.

The steady value of plate current (no signal impressed on the grid) for the 201A tube, with zero grid bias and 100 volts in the

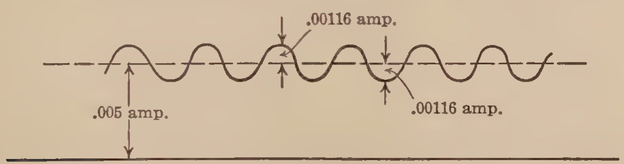

FIG. 68.—When an alternating voltage is impressed in the grid circuit the current flowing in the plate circuit has the form shown, the pulsations having the same form as the voltage impressed on the grid.

plate, would be about 0.005 ampere. The actual plate current therefore with one volt (effective) of alternating e.m.f. impressed on the input circuit would be as shown in Fig. 68. The dashed line shows the current in the plate circuit with no input signal, and the full wavy line shows the plate circuit current with one volt (effective) on the input circuit.

19. Uses of the Triode. Detector, Amplifier, Oscillator and Modulator.—The triode performs many roles in radio communication, in fact the whole development of radio has taken place around the vacuum tube.

As explained in Chapter III, radio communication must be accomplished by very high frequency currents, otherwise practically no energy is radiated from the transmitter. These fre-

quencies are far above the range audible to the human ear. The signal is carried by *low-frequency variations in the amplitude of the high-frequency current;* we need therefore at the receiving end of the radio channel a device which is responsive to high-frequency currents, and which will give a response corresponding to the *variations* of this current. The response will then be of audible frequency and if passed through telephone receiver will give the dots and dashes of a telegraphic code if such is being transmitted. Such a device, which gives a low-frequency response to a varying high-frequency current, is called a *detector*. It performs its function because of its rectifying qualities and is therefore suitably also called a *rectifier.* There are in use today two types of such rectifiers. Certain crystals, when in contact with a conducting point, or with another crystal, will serve the purpose and have much application in the cheap receiving sets. The triode, properly connected, also performs the function, more efficiently and reliably than the crystal, and the triode is used as detector in every good radio set.

The ordinary radio signal picked up by a small receiving antenna is 100 microvolts or less. This very low voltage, high-frequency signal, must be amplified, or strengthened, before being supplied to the detector, because the detector functions very inefficiently for voltages less than perhaps 0.1 volt. This means that the radio frequency signal picked up by the antenna must be greatly strengthened before being supplied to the detector. The power from the antenna is supplied to the input circuit of a triode; the output (fluctuations of plate current) of the triode is fed into the input circuit of another triode. This may be carried out for three or four steps, each step increasing the radio frequency power by perhaps 100 times. A triode used in this way, to **increase the power available**, is called an **amplifier.**

In the early days of radio the high-frequency currents required were set up by oscillatory discharges of condensers, or by very special machines. But, even so, satisfactory currents of very high frequency could not be obtained. Deforest, who invented the audion, also showed it possible to arrange the circuits in such a way that the triode (or *audion* as he called it), supplied with continuous current power, would generate alternating currents of practically any desired frequency. By suitably choosing the circuit constants the same triode will generate alternating current of any frequency from less than one cycle per second to 30 million

or more cycles per second. A triode so arranged that it transforms part of the continuous current energy with which it is supplied into alternating current energy is called an **oscillator.** A triode so used is the *only known method* of producing currents, of unvarying amplitude, of frequencies above about 500 kc.

At the radio transmitting station triodes are used as oscillators to supply the high frequency power to the antenna. Now to radiate an intelligible signal the amplitude (or frequency) of the radio frequency antenna current must be changed according to a definite code. If the station is a broadcasting station, the antenna current must be varied in amplitude according to the musical note of an orchestra or possibly according to the sound waves of the human voice. This task, of taking the few microwatts of sound of the voice, and making it control the amplitude of the antenna current in accordance with the sound waves to be transmitted, is performed by a suitably arranged triode; when so functioning it is called a **modulator.**

20. Need of a Rectifier in Radio.—To show the need of a detector, and how this must operate as a rectifier, we will consider

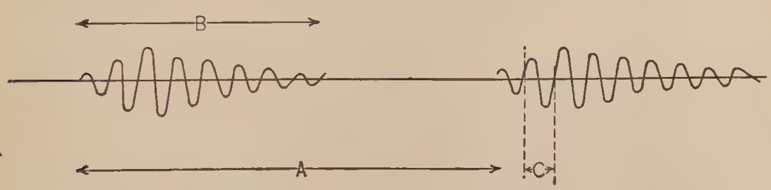

FIG. 69.—The voltage form of a spark, or damped-wave, signal.

the simplest type of radio signal, that sent out by a spark transmitter. As mentioned in Chapter III the received current in such a system consists of a series of damped, high-frequency currents. A typical form of current might be as shown in Fig. 69. The time A, from one wave train to the next, may be from 0.005 to 0.0005 second, the duration, B, of the wave train may be from 0.00001 to 0.001 second; and the time of one cycle, C, may be from 0.000001 to 0.00003 second. For one " dot " of a telegraph signal there would be from fifty to two hundred of the wave trains.

If such currents were to run through a telephone receiver the operator would receive no signal for two reasons; the diaphragm of the receiver could not appreciably oscillate at the high frequency

(perhaps 1,000,000 cycles per second) of the received current, and even if it did the human ear could detect no sound because the upper limit of audibility for the average adult is less than 15,000 vibrations per second.

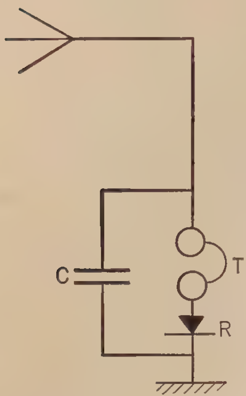

FIG. 70.—The simplest possible scheme of radio receiver.

If, however, there is a rectifying device in series with the telephone receiver, permitting current to flow in only one direction, then each wave train will give the telephone diaphragm one impulse. Thus, suppose the receiving antenna connected as in Fig. 70, the telephone receiver T is shunted by a condenser C to permit the high-frequency current to flow in the antenna circuit without meeting the high impedance of the telephone.

If the circuit were connected directly to ground without the rectifier R, conditions would be as shown in Fig. 71, there would be no diaphragm movement and hence no audible signal. On the other hand, if there is in the antenna circuit a device R which car-

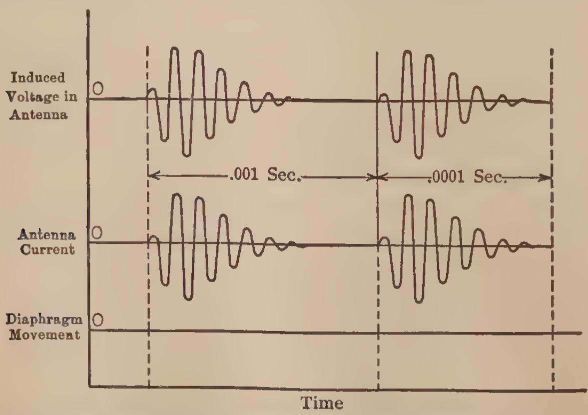

FIG. 71.—Showing that, without a rectifier in the receiver circuit, the spark signal produces no motion of the telephone diaphragm.

ries current more readily in one direction than in the other (that is, a more or less perfect rectifier) the conditions will be as depicted in Fig. 72, and the diaphragm of the receiver will receive one

impulse for each wave train. The result will be a vibration of the diaphragm *at the wave train frequency,* about 1000 per second

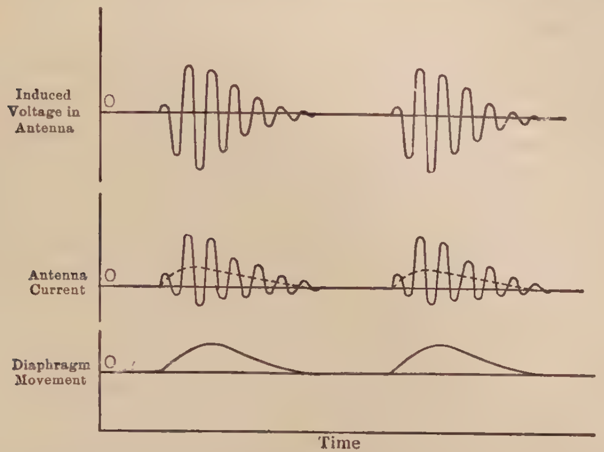

FIG. 72.—The action of the rectifier results in one impulse to the diaphragm for each wave train of the signal.

Thus it is evident that a rectifier is necessary to permit the radio-frequency currents to give an audible sound.

21. Triode as Detector.—The triode may be used as detector with, or without, a grid condenser (to be explained later). In Fig. 73 the triode is connected to a tuned receiving circuit, to be used as detector without grid condenser. Such a triode is said to detect by "plate rectification." Although not shown in Fig. 73, a condenser is practically always used in shunt with the telephone to by-pass the high-frequency pulsations of plate current.

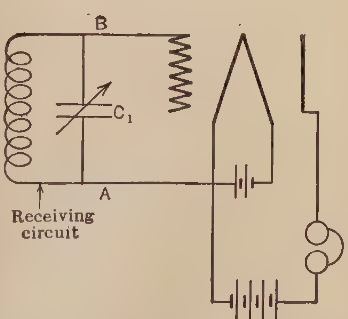

FIG. 73.—Connection of triode, to bring about the results depicted in Fig. 72.

As the grid potential goes up and down, under the action of the radio signal, the plate current must increase and decrease according to the characteristic of the triode (see Fig. 57, p. 111, or Fig. 58, p. 113).

In Fig. 74 there is shown in the dashed curve the plate current of the triode of Fig. 73, as a function of the grid potential. As one of the wave trains of Fig. 71 is impressed on the grid, its potential follows the curve 1, 2, 3, 4, . . . 14, 15 of Fig. 74. Corresponding to each potential on the grid a definite value of plate current must

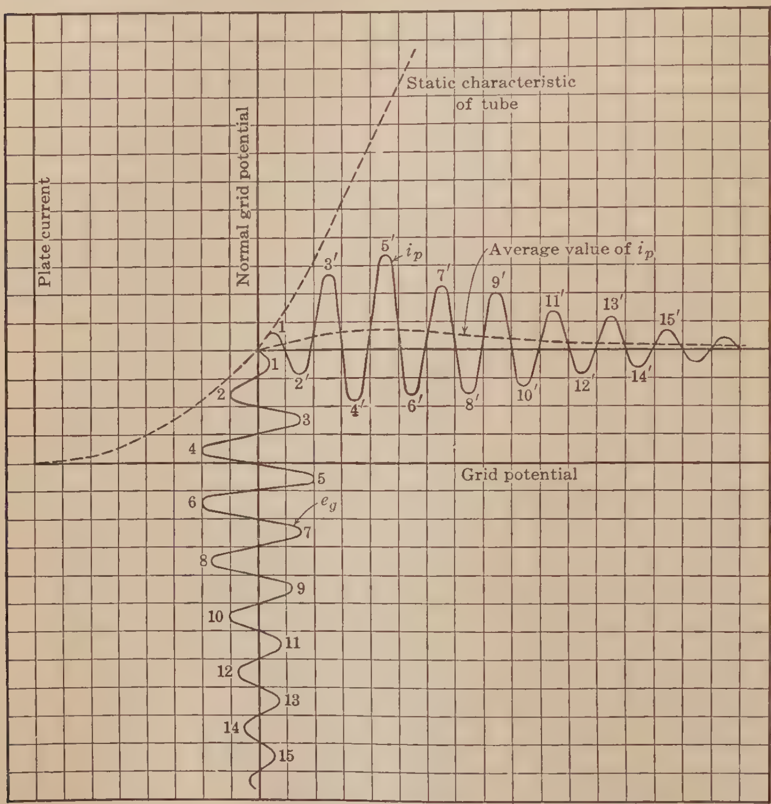

FIG. 74.—When using "plate-circuit rectification" the radio signal in the input circuit causes an *increase* in the average value of the plate current.

flow; the plate current is then given by the curve, 1′, 2′, 3′, 4′ . . . 14′, 15′. It can be seen from this curve that the *increases in plate current, when the grid goes positive, are greater than are the decreases in plate current when the grid goes negative.* This results in an average plate-circuit current as shown by the dashed curve marked "average value of i_p."

From this curve sheet it is seen that one wave train of high-

frequency voltage on the grid of Fig. 73 will produce a somewhat similar high-frequency fluctuation in plate current. The high-frequency fluctuation, however, contains greater increases than decreases, resulting in the net increase shown by the dashed line. Hence the telephone receivers of Fig. 73 will receive one impulse of current for every high-frequency wave train on the grid.

By utilizing a somewhat different action of the triode it is possible to obtain more efficient action as a detector. The triode is connected to the receiving circuit as shown in Fig. 75. Between the grid and receiving circuit there is a condenser C, generally about 200 $\mu\mu f$. Such use of a condenser would leave the grid elec-

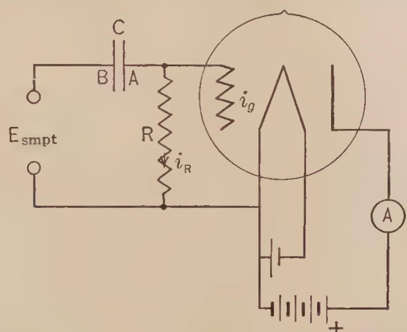

FIG. 75.—A triode arranged for detection by "grid-circuit rectification" utilizes a grid condenser and grid leak in the input circuit.

trically free; it would be insulated from all other parts of the circuit. Such a "floating" or "free" grid would result in very erratic performance of the triode. To remedy this condition a high resistance, R, generally a megohm or more, is connected between the grid and filament circuit. Such a high resistance permits the grid to change its average potential under the action of an impressed signal, but after this has ceased to act the grid is constrained to return to its proper potential by the action of this **grid-leak resistance,** as it is called.

The action of the grid condenser and grid leak is somewhat as follows: the signal voltage, acting on the grid through the condenser C (Fig. 75), makes the grid go alternately positive and negative with respect to the value it has when no signal is coming in. In Fig. 76 this is shown as the voltage E_{og}, slightly negative. The characteristic curves of the triode are shown by the two curves

c, a, d, b and *e, g, h, f*. The former shows the current taken by the grid, as the grid potential is varied, and the latter shows the plate current as the grid potential is varied.

We suppose a sine wave signal, of amplitude E, is impressed on the grid, marked "signal (start)." With no signal coming in the

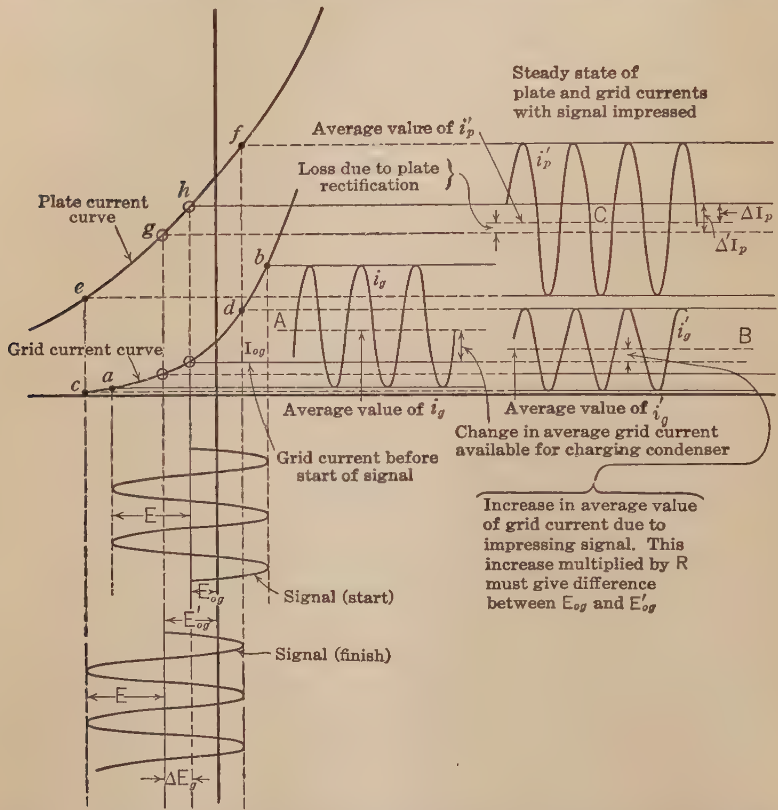

FIG. 76.—This set of curves shows that due to grid rectification the average grid potential decreases when the radio signal is impressed; this causes a *decrease* in the average value of the plate current.

grid current was steady at the valve I_{og}. With the signal voltage impressed on the grid, a corresponding variation in grid current flows, shown in Fig. 76 by the curve i_g. It can be seen that there is a much greater *increase in grid current with positive signal voltage on the grid than there is decrease in grid current with negative signal voltage on the grid.* Thus, there is, on the average, an increase

in the supply of electrons to the grid and so more electrons become stored on the plate A of condenser C (Fig. 75). As more electrons become stored on plate A its potential goes down (electrons being negative charge) so there is a greater current through the grid leak R. Thus the potential of the grid is depressed by the signal to the value marked (on Fig. 76) E'_{og}. Then if the signal continues, the grid current is as represented by i'_g in Fig. 76 and the corresponding plate current is shown by i'_p. Now before the signal was impressed on the grid the plate current had the value shown on the plate-current curve at h. After the signal has depressed the grid potential to E'_{og} the average plate current corresponding is shown at g.

The average plate current is somewhat larger than this value while the signal is acting because the curvature of the plate-current curve tends to give an increase in i_p. Thus the actual average decrease in plate current is somewhat less than the difference of the values shown at h and g; the plate rectification tends to neutralize the grid rectification. However, the grid rectification predominates and there occurs an actual decrease in the average value of the plate current, as shown at ΔI_p in Fig. 76. If there were no plate rectification the decrease in average plate current would be as shown at $\Delta' I_p$.

In the ordinary receiving triode, used as detector with no grid condenser, the average plate current changes 1 microampere for a radio frequency signal of about 0.2 volt whereas if suitable grid condenser and grid leak are used only one-third as much signal voltage is required for the same change in plate current. In Fig. 77 there are shown oscillograph records of signal voltage, plate current, and current through the telephone, for a triode detecting with grid condenser and grid leak. Of course the circuit used in getting this record had frequencies much lower, with inductances and capacities much larger, than those used in actual radio circuits. This was necessary to permit the oscillograph vibrator to follow the fluctuations of current.

From the record it can be seen that just as soon as the signal voltage ceases, the charge which has accumulated on plate A of condenser C (Fig. 75) leaks off, permitting the grid potential to increase again to its normal value, with a corresponding increase in the plate current. The rapidity with which the grid potential resumes its normal value depends upon the product of the values of leak resistance and grid-condenser capacity. If this product

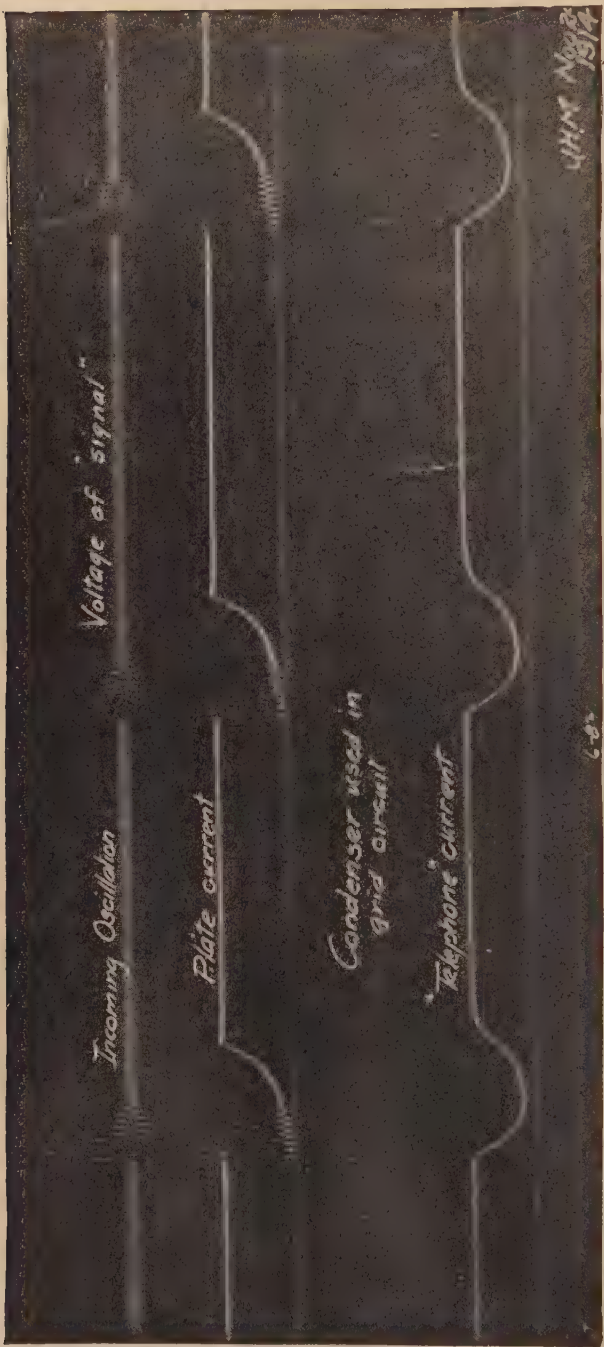

FIG. 77.—Oscillogram to show the action of the grid condenser and grid-leak method of detection. The plate current has ripples of the frequency of the signal in the grid and in addition has a large decrease in its average value. The condenser shunted around the telephones takes the high-frequency ripple current, and the low-frequency dip in the plate current flow through the telephones.

is too large the grid potential cannot change rapidly and its detector action becomes imperfect. In Fig. 78 is shown the action of the same circuit as was used in getting the record of Fig. 77, after the resistance of the grid leak had been increased three times. It will be seen at once that it took the grid a much longer time to resume its normal potential after the signal had ceased.

In both Fig. 74 and Fig. 76 it can be seen that the damped-wave signals impressed on the grid of the triode, used as a detector, give in the plate circuit one pulse in the plate current for each wave train of the signal and also that the plate current has high-frequency

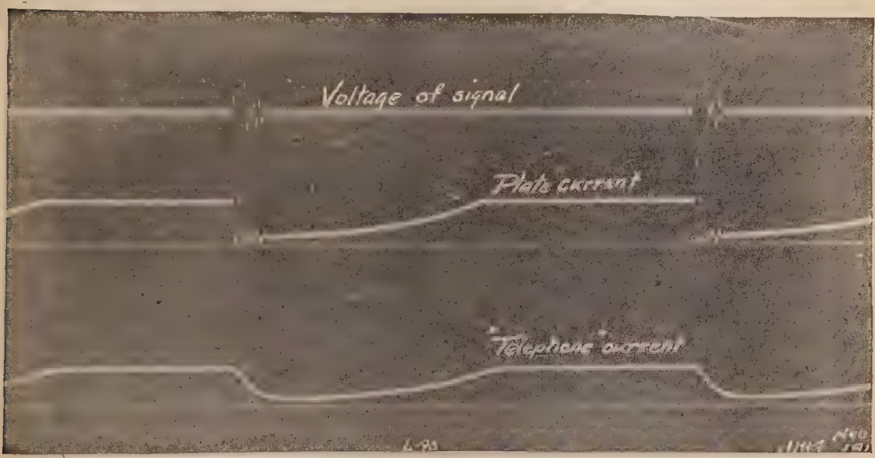

FIG. 78.—This film shows the action of the circuit used for Fig. 77, after the resistance of the grid leak had been increased about three times.

pulsations of the same frequency as the signal. These high-frequency pulsations would encounter tremendous impedance if they were forced to flow through the telephone receivers; it is the function of the condenser, generally shunted around the phones, to by-pass these high-frequency currents. The telephone current is then a direct current with smooth "dips," one dip for each wave train of the signal, as shown in the lower record of both Figs. 77 and 78.

22. Triode as Amplifier.—In its role as amplifier the triode performs even more important service than when being used as detector; there are other devices which work reasonably well as detectors but there is no device of any kind that even approaches

the triode as an amplifier. Small fluctuations in the grid potential produce changes in the plate current of much greater magnitude than if these grid voltages were introduced directly in the plate circuit; furthermore if the grid potential is sufficiently negative it accomplishes the control of the plate current with the consumption of practically no power in the grid circuit.

The equation of current in the plate circuit was given in eq. 48, p. 110.

$$I_p = K(E_p + \mu E_g)^x.$$

Thus the relation between plate current and grid potential (plate potential held constant) is a curvelinear one, but as is true of any smooth curve, if the plate current has only small fluctuations the relation between grid voltage and plate current may be considered a straight line, that is, the change in plate current is directly proportional to the change in grid voltage, provided always that the change in plate current is small compared to the actual magnitude of plate current. Thus if the plate current of a triode is 10 milliamperes, and an increase of grid potential of 4 volts changes it to 11 milliamperes we may consider the change in plate current small and hence conclude that a change in grid voltage of 1 volt will change the plate current by one-quarter of a milliampere, or that a change of grid voltage of 2 volts would change the plate current by $\frac{1}{2}$ milliampere.

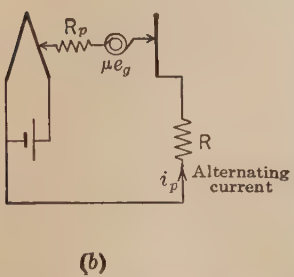

Fig. 79.—A diode circuit which is equivalent to a triode circuit with a signal voltage of e_g impressed.

We now consider the triode replaced by an equivalent diode, in the plate circuit of which there is introduced a voltage μ times as great as the voltage impressed on the grid of the triode. This is done in Fig. 79 in which R represents the resistance in the external plate circuit and R_p represents the alternating current resistance of the plate circuit inside the triode. This is, as shown in Fig. 63, p. 117, practically one-half of the direct-current resistance of the plate circuit.

By inspection of Fig. 79 we at once get the relation

$$I_p = \frac{\mu E_g}{R_p + R}, \qquad \qquad (54)$$

in which I_p = effective value of alternating current in plate circuit;
E_g = effective value of alternating voltage on grid.

Then the alternating voltage drop across the resistance R is available for repeating into another triode by proper connection. This voltage is

$$I_pR = \mu E_g \frac{R}{R_p + R} = E_g\left(\mu\frac{R}{R_p + R}\right). \quad . \quad . \quad . \quad (55)$$

Evidently the factor $\mu\frac{R}{R_p + R}$ may be much greater than unity, that is, the output voltage of the triode is greater than the input voltage. It is thus a voltage amplifier; by making the external

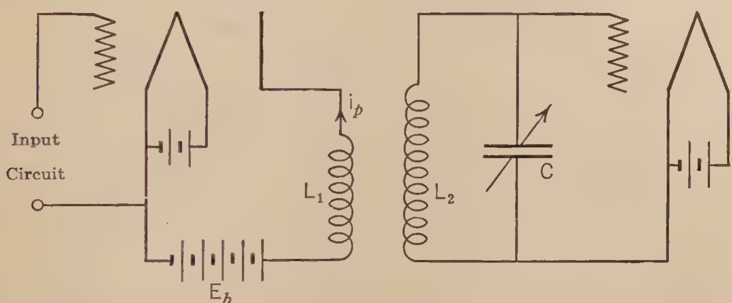

FIG. 80.—Normal arrangement of a triode circuit for selective amplification of a radio-frequency signal.

resistance R large compared to the internal resistance R_p the actual amplification can be made almost equal to the amplification factor of the triode.

The external part of the plate circuit of a triode is generally made up differently if the signals to be amplified are of radio frequency than if they are of audio frequency. For a radio frequency amplifier the circuit is generally arranged as in Fig. 80. A coil L_1, of a few microhenrys, is coupled about 50 per cent to another coil L_2 of about 200 μh and a variable condenser C of about 400 $\mu\mu f$ maximum capacity. These values are suitable for the frequencies employed in radio broadcasting. The fluctuations in plate current, i_p, through coil L_1 set up a voltage in the circuit L_2–C, which is tuned to the desired frequency. In the ordinary radio-frequency

amplifier the voltage across C will be about 10 times as great as the voltage impressed on the input circuit. For frequencies not close to that for which the circuit is tuned the arrangement gives a voltage across C actually less than the input voltage. It is thus a **selective amplifier,** magnifying the desired signal and eliminating others.

If the triode is to be used as an amplifier of audio frequencies it cannot well use a tuned output circuit. To amplify speech clearly, for example, *all of the frequencies* of the voice must be magnified in the same proportion. For truthful amplification of speech or orchestra music, therefore, the circuit must be arranged to give

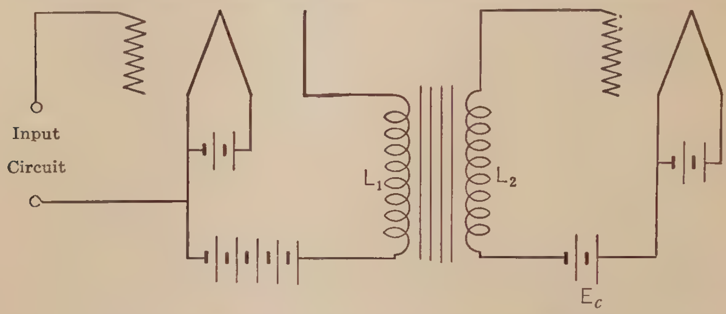

FIG. 81.—Normal arrangement of a triode circuit arranged for non-selective amplification of audio frequency signals.

flat amplification over the frequency range from 50 to 6000 vibrations a second. The lower limit is needed for organ music and the upper one for the consonants of the voice. The circuit used is shown in Fig. 81. An iron core transformer is always used, with the two coils coupled as closely as possible. To amplify the low frequencies the coil L_2 must have an inductance of 50 henrys or more. A step up ratio of about 3 to 1 is permissible; this will give a secondary coil of about 500 henrys. If the secondary coil has more inductance than this the high frequencies are likely to be lost, through the internal capacity of the winding.

In this type of amplifier it is very important that the grid of the triode, to which the voltage of the transformer is supplied, does not draw current. This means that the grid must not go positive, even when the signal is coming in. So a battery E_c (called the C battery) is used; the *voltage of this battery should be greater than the voltage of any signal the circuit will have to handle.*

23. Possible Output of an Amplifier Triode.—In general the last triode of an amplifier arrangement has to supply sufficient power to operate a loud-speaking telephone. The other triodes of an amplifier have to handle comparatively little power so that their possible power output is of little importance.

The possible alternating-current power output of a triode is fixed by the product of the voltage used in its plate-circuit supply and the average value of the plate current. The theoretical limit of output is equal to half this product. Thus a triode with a plate-voltage supply of 300 and a plate current of 20 milliamperes has a limiting output of $\frac{1}{2}$ $(300 \times 0.02) = 3$ watts.

But the quality of the signal supplied to the loud speaker would be very poor; it would be greatly distorted from the true signal. As some distortion is always present, even with small power outputs, the possible output of a triode depends altogether upon the allowable amount of distortion. A reasonable rule indicates that the rated output of an amplifier tube should not be more than 5 per cent of its theoretical limit, determined as above.

24. Triode as Oscillator.—As explained in Chapter III, Section 2, it is necessary to use in the antenna of a radio transmitter very high-frequency currents, otherwise practically no power is radiated. For the large trans-oceanic radio telegraph stations frequencies from 20 kc. to 40 kc. are customary. Such frequencies can be generated reasonably well by rotating machinery. For ship radio sets, and for broadcasting purposes, frequencies from 500 kc. to 1500 kc. are used and, as mentioned in Chapter III, frequencies up to 30,000 kc. are becoming of ever-increasing importance. For these higher frequencies (above 50 kc.) the oscillating vacuum tube is most suitable, and furthermore this is practically the *only means* of getting this high-frequency power.

The fact that the triode, supplied with continuous-current power in its plate circuit, may be arranged to generate alternating current power is credited to Deforest, who invented the triode itself. The simplest scheme for making the triode oscillate is shown in Fig. 82. The plate circuit of the triode consists of a coil L_1, having resistance R_L, shunted by a condenser C. In the grid circuit there is a coil L_2 which is magnetically coupled to the coil L_1.

If L_2 is coupled to L_1 sufficiently closely, and connected to the grid in the right direction (to be explained later) alternating current

will be set up in the L_1-C circuit and will continue to flow as long as the filament and plate batteries last.

The frequency of the alternating current is the natural, or resonant, frequency of the circuit L_1-R_L-C. We know that this frequency is given by the relation

$$f_r = \frac{1}{2\pi\sqrt{L_1C}},$$

and it therefore appears that by properly choosing L_1 and C the frequency may be anything desired. By using the circuit of Fig.

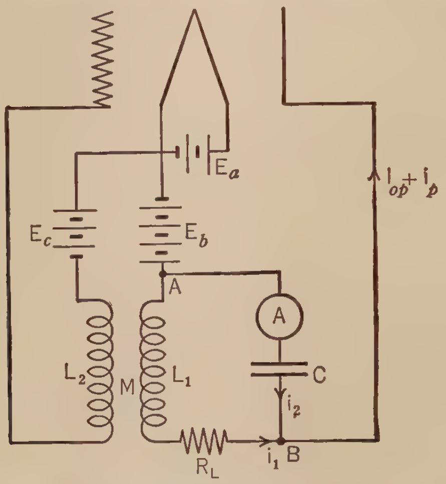

FIG. 82.—A simple circuit arrangement for producing oscillations by means of a triode.

82 and properly choosing the coils and condenser, the same triode will generate frequencies anywhere from one per second to possibly 60,000,000 per second. Specially constructed triodes have been made to generate frequencies as high as 300,000,000 per second.

Starting with very weak coupling between L_1 and L_2 it will be noticed that there is no current in the L_1-C circuit (shown by reading of ammeter A) until the coils L_1 and L_2 reach a certain critical coupling. Here the circuit suddenly begins to oscillate, and develops a current in the oscillating circuit many times larger than the plate current itself. The current in the oscillating circuit L_1-C is limited only by R_L and L_1 itself. As both of these are lowered the current in the oscillating circuit increases. A limit in

diminution of L_1 is soon reached, however; if it is made too small the circuit will not oscillate at all.

It may be found that no matter how closely L_2 is coupled to L_1 no oscillations occur. This indicates that L_2 is connected in the wrong direction. By either reversing the coil L_2, end for end, or leaving it as it is and interchanging the grid and filament connections to it, the circuit will begin to oscillate. There are, of course, certain general considerations which must be satisfied. Thus L_1 and L_2 should be of about the same value, R_L must be kept reasonably low, and the condenser C must be reasonably low compared to the coils used. This latter consideration will generally be satisfied if *the condenser capacity in micro-microfarads is not greater than the inductance of the coils in microhenrys.*

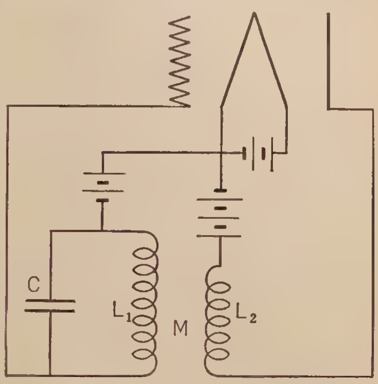

FIG. 83.—Another circuit arrangement for producing oscillations; in this circuit L_2 is called the "tickler" coil.

There are many other arrangements of coils and condensers which are used to produce oscillations; all of them operate in such a way that a change in plate-circuit current induces a voltage on the grid, and the polarity of the connections is always such that when the circuit is oscillating the grid potential goes up as the plate potential falls. That is, the phase of the alternating grid voltage must be 180° away from the phase of the alternating plate voltage. In Fig. 83 the oscillating circuit is connected to the grid; the coil L_2, in the plate circuit, serves to excite the grid circuit and maintain the oscillations. This coil L_2, used in this way, is generally called the " tickler " coil.

In Fig. 84 are shown two well-known schemes for producing oscillation. In (*a*) the oscillatory circuit is made up of the coils L_1 and L_2, in series with the condenser C. The condenser C_1 is also in the oscillating circuit but it is really a by-pass condenser around the B battery. Its capacity may be a microfarad whereas that of C will be only one-thousandth as much, so C_1 plays practically no part in fixing the frequency.

In (b) of Fig. 84 the oscillating circuit consists of C_1 and C_2 in series, and the coil L. The arrangement is somewhat more complicated than the others, but is useful in certain transmitting circuits. The condenser C_3 is an insulating condenser to keep the high positive potential of the plate from the grid. The grid being thus insulated from the rest of the circuit requires the leak resistance R to maintain it at a proper potential. The coil L_2 is a choke coil to prevent the radio frequency power flowing through the B battery. It will be understood that except for very small power triodes the B battery is replaced by a high-voltage continuous-current machine, or a rectified alternating-current power supply.

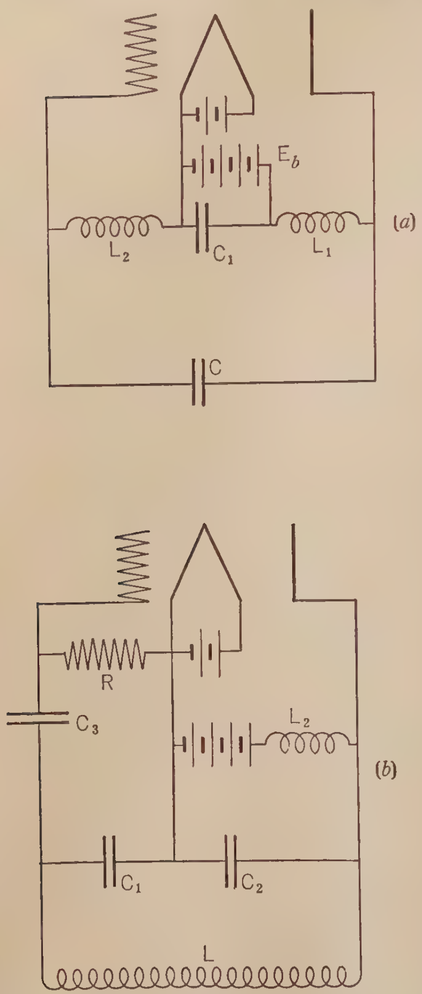

FIG. 84.—Two other arrangements frequently used for producing oscillations.

In the arrangement of (a), Fig. 84, the two coils L_1 and L_2 should be about equal; they are generally two insulated sections of the same solenoid. In (b) of Fig. 84 the two condensers C_1 and C_2 should be about equal and the condenser C_3 should generally be several times as large. The coil L_2 should have much more inductance than the coil L.

The efficiency of the triode operating as an oscillator is from 25 to 40 per cent in the average case. This means that 25 or 40 per cent of the power delivered to the triode plate circuit by the B battery is changed into alternating-current power. Thus

a small tube drawing 0.06 ampere plate current from a 350-volt power supply is using 21 watts. Such a tube will, when proper adjustments to its circuit have been made, generate about 5 to 8 watts of alternating-current power.

25. Heating of Plates.—The electrons which evaporate from the filament and are pulled over to the plate by its positive potential, attain enormous velocities, before they have traveled the short distance between them. Thus if the plate voltage is 22 (as it is in the average detector tube) the electrons, when they strike the plate, are moving at the rate of about 1600 miles per second and in an amplifier tube using 100 volts on the plate the electrons hit the plate with a velocity about 3500 miles per second. In the larger power tubes, using 20,000 volts on the plate, the electrons, when they strike the plate, are moving with the inconceivable velocity of 50,000 miles per second.

When they strike the plate these rapidly moving electrons are suddenly stopped and give up their kinetic energy of motion to the plate. This energy appears in the plate as heat, in the larger tubes in very great amount.

A small power tube such as is rated at 10 watts, or the somewhat larger one rated at 50 watts, when operating as oscillators, have developed on their plates as heat, energy at a rate about the same as their watt rating. The rate at which the electron bombardment develops heat on the plate can be calculated from the product of the plate voltage and plate current, if the tube is not oscillating. Thus a tube having 350 volts on its plate, and drawing from its plate-circuit power supply 60 milliamperes, develops heat on its plates at the rate of $350 \times 0.06 = 21$ watts. If the tube is oscillating, under average conditions of adjustment, the heating of the plates is given by somewhat more than *one-half* the product of plate volts and plate current, read by continuous-current meters.

26. Water-Cooled Tubes.—In a large power tube the plate voltage may be 20,000 and the plate current 5 amperes. When this tube is oscillating the heat developed on its plate is about 50 kw. and if it is not oscillating 100 kw. are being expended in heating the plate. Now as the plates, of even the largest tubes, have an area of only a few square inches (possibly 100–200) it is evident that the plates cannot possibly carry off the great amount of heat by radiation and the slight conduction along the supporting wires. Even in the smaller tubes (5–250 watt rating) the plates glow a dull

red when the tube is operating at rated power. Above these ratings the heat sent off from the plates would be sufficient to melt the glass of the triode; other methods must be employed to carry the heat away from the plates.

By making the tubes in the form shown conventionally in Fig. 85, the plate constitutes part of the wall of the triode. A heavy copper tube *A*, closed at its lower end, is drawn down to a feather edge along its upper edge, *B*, and here is sealed on to the glass tube, *C–C*. The filament, *F*, consisting of one or more hair-pin loops of heavy tungsten wire, and surrounded by the spiral grid, *G*, is inside the copper tube. *The tube A is then the plate* and being thus constructed can be immersed in a tank of water for cooling purposes. A whole battery of such water-cooled triodes is shown in Fig. 86. Each triode is immersed in a small cylindrical tank, the ridge *K* (Fig. 85) resting on the top edge of the tank. Cooling water is forced through these tanks and thus the plates are kept reasonably cool, in spite of the many kilowatts of power being expended on them. The group of triodes shown in Fig. 86 is used in a trans-Atlantic radio telephone transmitting station.

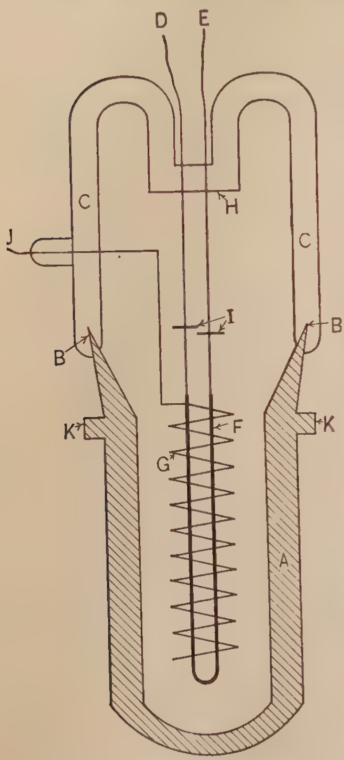

FIG. 85.—Conventional diagram of a water-cooled tube.

As the water supply is generally grounded and the plates, in contact with the water, are many thousand volts above ground potential the water is passed through a long rubber hose between the triodes and supply tank; furthermore water free from dissolved salts must be used or else excessive leakage of current will occur from plate to ground.

These large water-cooled triodes have automatic devices to cut off the power supply to the plates immediately if the water supply fails or the temperature of the cooling water gets too high.

27. Calculation of Oscillatory Circuit.—If the characteristics of a triode are known it is possible to predict whether or not it will oscillate when connected to a specified circuit. In general the derivation of the solution for the oscillatory condition requires the use of differential equations, but one or two typical cases will be discussed here without trying to derive the solution.

In the arrangement of Fig. 87 let the alternating resistance of

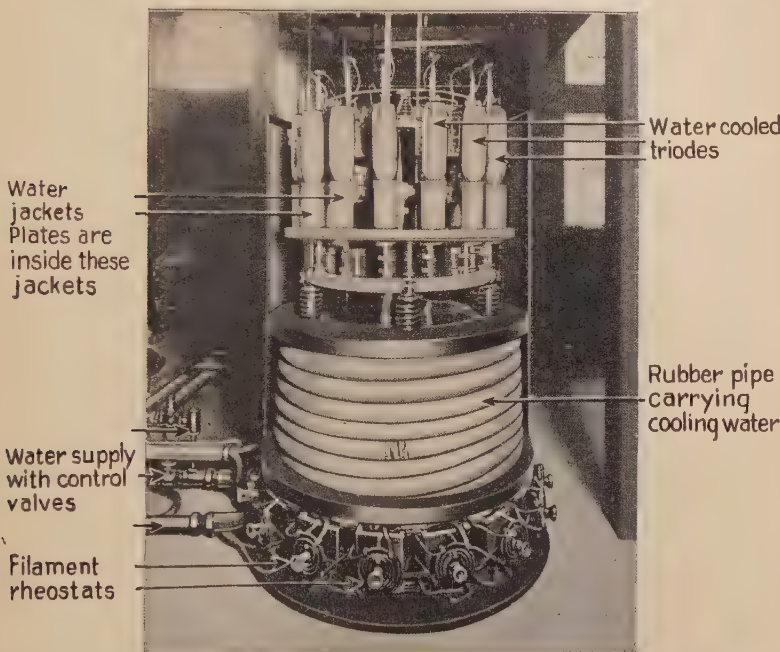

FIG. 86.—A battery of water-cooled tubes, each of 20 kw. rating, used for trans-Atlantic telephony.

the plate circuit be R_p and let the amplification constant of the triode be μ. As mentioned in Section 24, p. 137, the coil L_2 must be arranged with proper polarity if oscillations are to be set up. If the circuit does not oscillate when L_1 and L_2 are closely coupled the connections of L_2 to grid and filament should be reversed.

Having L_2 thus connected with proper polarity, this circuit will oscillate if the relation is satisfied that

$$M > \frac{1}{\mu}(L_1 + CRR_p). \qquad (56)$$

This solution indicates that the higher the μ of the tube the smaller is the required M to produce oscillations. If with oscillations set up, C or R are increased, the oscillations may stop. Or if R_p is increased by decreasing the plate voltage (see section 16, p. 116) the inequality 56 may not be satisfied so that decreasing the plate voltage of an oscillating triode may stop the oscillations.

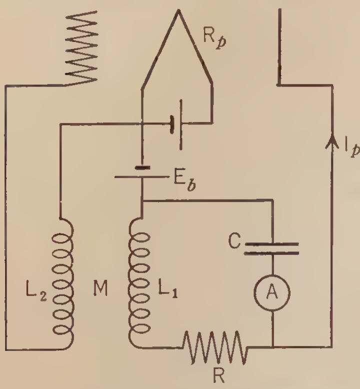

FIG. 87.—One circuit arrangement for which it is comparatively easy to deduce the conditions required to produce oscillations.

As an illustration let us suppose that, in Fig. 87, $L_2 = 100\mu h$, $L_1 = 200\mu h$, $R = 40$, $C = 0.001\mu f$, $\mu = 8$, $E_b = 300$ and I_p (continuous current) $= 0.05$. What coupling must be used between L_1 and L_2 to produce oscillations?

We first find R_p. From section 16, p. 116, we know that R_p is approximately one-half the value of R_{op} which in turn is the quotient of the voltage E_b and current I_p (continuous current). This gives $R_{op} = 6000$ ohms, then $R_p = 3000$ ohms. Then M must be greater than

$$\tfrac{1}{8}(200 \times 10^{-6} + 0.001 \times 10^{-6} \times 40 \times 3{,}000)$$

$$\text{or} \quad M > \tfrac{1}{8}(320 \times 10^{-6}) \quad \text{or} \quad M > 40\mu h,$$

and as

$$K = \frac{M}{\sqrt{L_1 L_2}},$$

we have finally for the minimum coupling to produce oscillations

$$K = \frac{40}{\sqrt{100 \times 200}} = 28.3 \text{ per cent.}$$

Let us now consider the case of Fig. 88, where the oscillating circuit is in the grid. In this case the solution of the differential equation of the circuit yields the condition that, to produce oscillations, we must have very nearly the relation

$$M > \frac{\mu L_1}{2} - \sqrt{\left(\frac{\mu L_1}{2}\right)^2 - RR_pL_1C}. \quad . \quad . \quad . \quad (57)$$

If we now use the same coils and condenser as used for Fig. 87, as well as the same triode, we find that M must be greater than

$$\frac{8 \times 200 \times 10^{-6}}{2} - \sqrt{\left(\frac{8 \times 200 \times 10^{-6}}{2}\right)^2 - (40 \times 3{,}000 \times 200 \times 10^{-6} \times 0.001 \times 10^{-6})} = 15\mu h.$$

Then for the coupling to produce oscillations we shall have

$$K = \frac{15}{\sqrt{200 \times 100}} = 10.7 \text{ per cent}$$

so that oscillations would occur more readily with the oscillating circuit connected to the grid than when connected to the plate.

Many other oscillatory circuits can be figured as were the two given above; more extensive texts should be consulted for other solutions.

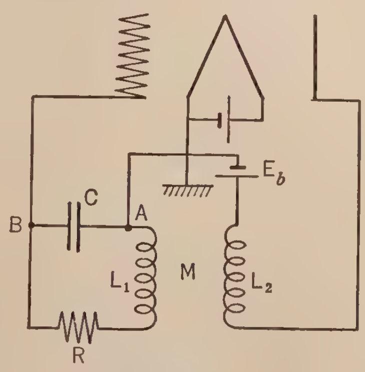

FIG. 88.—Another circuit for which the criterion for oscillations may be mathematically deduced.

28. How to Detect Oscillations.—In the circuit of a transmitting set the amount of alternating current being generated is indicated by ammeters, properly placed. Thus in the circuit of Fig. 87, if the ammeter A reads, there must be alternating current generated; the ammeter being directly in series with the condenser C could read only alternating current. If the ammeter were placed in the coil branch of the oscillating circuit, it would read even if the circuit were not oscillating, because the plate current flows through this branch of the circuit. In case the ammeter is in the coil branch and the circuit is oscillating, producing current of effective value I, and the steady component of the plate current is I_p then the ammeter will read $\sqrt{I^2 + I_p^2}$. As I_p is generally small compared to the alternating current this reading is practically the same as I. It follows then that the meter will give practically the same readings whether it is connected in the coil branch or the condenser branch of the circuit.

In many cases a receiving set requires an oscillating triode; in such a case the oscillations cannot be detected by an ammeter because the amount of alternating current is altogether too small to be read on the ordinary ammeter. The oscillating receiving tube nearly always uses the circuit of Fig. 88; the amount of alternating current in the L_1–C circuit may be less than a milliampere, so would require a delicate and expensive ammeter for measurement. In the receiving tube the amount of alternating current generated is generally of little importance; the question to be determined is merely, is it oscillating?

To determine whether the circuit is oscillating a simple test suffices: There will generally be a telephone receiver in the plate circuit and its indications serve to answer the question. With the thumb touching the circuit at A, Fig. 88, that is, at the filament terminal, the finger is touched to B, that is the grid side of the oscillating circuit. If the circuit is oscillating there will be a click in the phones when the finger is touched to B, and another click when it is removed. If no click is heard, the circuit is not oscillating.

If the circuit is not oscillating it may be made to oscillate by increasing the coupling between the tickler coil L_2 and the coil L_1. Of course, as has been stated before, L_2 must be coupled to L_1 with the right polarity. If one listens carefully as the coupling is increased a slight " plucking " sound may be heard in the phones, as the critical value of coupling is passed and oscillations begin. This test for oscillations is not as reliable, for the unskilled listener, as the finger test described above.

29. Undesired Oscillations.—It very frequently happens that a triode, with its amplifying circuit, generates oscillations when these are not wanted; that is, in arranging the circuit for efficient amplification (especially for radio-frequency amplification) the conditions have accidentally been satisfied for producing oscillations. In an amplifying circuit not intended for oscillations, the presence of such oscillations will generally manifest itself by the amplifier being almost " dead," in so far as amplification is concerned, as well as by disagreeable " whistles " and howls in the loud speaker.

One circuit which has been much used for producing oscillations in a triode is shown in Fig. 89. The oscillatory circuit consists of L_1 and L_2 in series with condenser C. Condenser C_1 is a

by-pass condenser to permit the high-frequency currents to find a low impedance path around the B battery. The feed-back of energy from plate to grid, which is required to maintain oscillations in any circuit, is not magnetic as it was in Figs. 87 and 88; the two coils L_1 and L_2 of Fig. 89 are not coupled together at all. But it will be seen that condenser C couples the plate to the grid, and it is the coupling furnished by this condenser that permits the maintenance of the oscillations. As the capacity of the coupling condenser C is diminished the coupling of the two circuits is also diminished, but if the coils L_1 and L_2 are of suitable inductance, and low resistance, it will be found that oscillatory currents flow in plate and grid coils *even after C has been completely removed.*

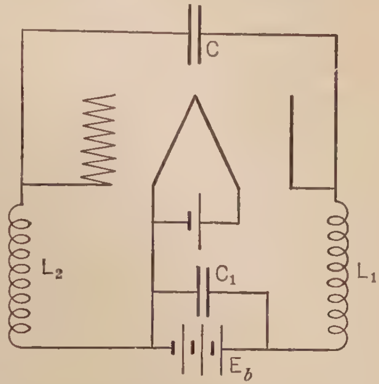

FIG. 89.—An oscillatory circuit in which the feed-back coupling is through the condenser C, connected to plate and grid.

The reason for such occurrence lies in the fact that even when C has been removed there is still some coupling capacity left in the circuit, namely that of the condenser formed by the grid and plate of the triode. In the average amplifier tube of today this grid-to-plate capacity is from 5 to $10\mu\mu f$ and *this is sufficient to maintain oscillations* in the circuit made up of this capacity (inside the triode) with L_1 and L_2 in series. Such oscillations are undesired and interfere seriously with the performance of a radio-frequency amplifier. With the coils used in the average broadcast receiver, and the grid-plate capacity of the average triode, these spurious

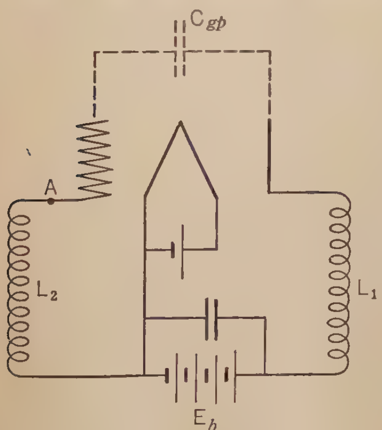

FIG. 90.—Even though the condenser C of Fig. 89 is omitted there is always some capacity connected in this fashion; the actual capacity between plate and grid elements of the triode itself forms such a condenser.

oscillations (sometimes called *parasitic oscillations*) have a frequency of about 4000 kc.

30. Prevention of Parasitic Oscillations.—As these oscillations are caused by the capacity between the grid and plate of the triode, and as they use the grid-plate capacity as the condenser of their oscillatory circuit there are at least two evident remedies. The first is to put a high resistance in the oscillatory circuit made up of L_1, L_2 and C_{gp} (Fig. 90). But this resistance must not be so placed in the circuit that it interferes with the normal performance of the amplifier in selecting one signal from another. Generally the grid coil L_2 of Fig. 90 forms part of the normal tuned circuit of the receiver and its resistance must be kept as low as possible. The plate coil L_1, however, is practically never part of a tuned circuit, so its resistance may be increased many times without interfering with normal tuning. Hence one remedy for parasitic oscillations is to make L_1 of very fine wire of some high-resistance alloy, such as *Calido*.

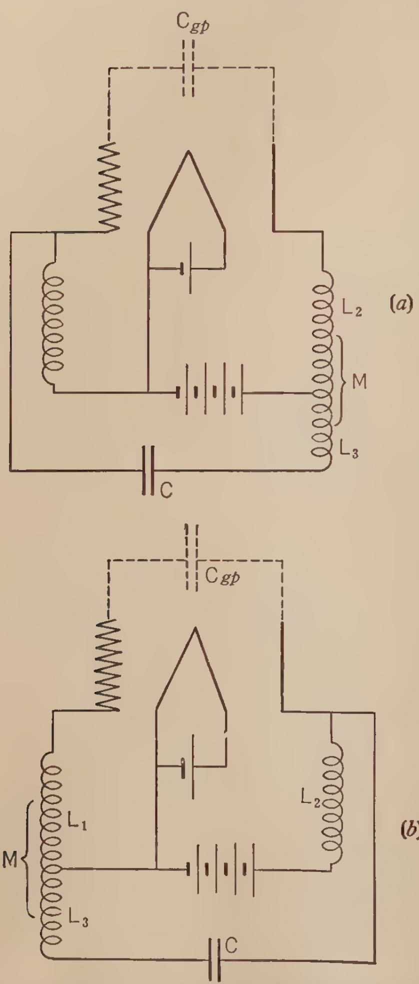

FIG. 91.—Two circuit arrangements for neutralizing the oscillatory tendency caused by the grid-plate capacity of the triode.

Another remedy is to insert a high resistance (perhaps 1000 ohms) in the grid connection, as at A in Fig. 90. The high-frequency oscillations will have to flow through such a resistance and the amount of coupling

offered by the grid-plate capacity is not sufficient to sustain oscillations through such a high resistance. Both eqs. 56 and 57, it will be noticed, show that higher coupling is required as the resistance of the oscillatory circuit is increased.

Another method of preventing undesired oscillations is indicated in Fig. 91. An additional coil L_3 is inserted in the circuit and this coil is closely coupled to either L_2 or L_1. In (*a*) of Fig. 91 it is coupled to L_2. A condenser C is connected between the end of this coil L_3 and the grid. If the coil L_3 is properly coupled to L_2 and C is of suitable capacity then the L_3–C combination will produce on the grid a voltage just equal and opposite to that produced by the L_2–C_{gp} combination. Hence the two effects will just neutralize one another and no oscillations will occur. The condenser C is generally made adjustable and is brought to its proper value after the set has been assembled.

In (*b*) of Fig. 91 exactly the same principal is used as in (*a*) but here the extra coil L_3 is closely coupled to the grid coil L_1 and the capacity C is connected to the plate. Other combinations have also been used but they all operate on the same principle, namely, the grid-plate coupling between the grid and plate circuits is offset, or neutralized, by another coupling effect of equal magnitude and opposite phase.

31. The Screen Grid Tube.—Still another method of getting rid of the undesired coupling effect between grid and plate of the ordinary triode is now available. It has been found possible to interpose another grid between the plate and normal grid of the tube and to connect this extra grid to the circuit in such a way that the capacity effect between the plate and normal grid is brought to practically zero. This extra grid is called the **screen grid**; its function is to screen the normal grid (or **control grid** as it is called) from the electro-static effects of the plate. It takes the form of a fine spiral of wire held in place between the plate and control grid. To make its action more complete, it has another spiral which is placed out-

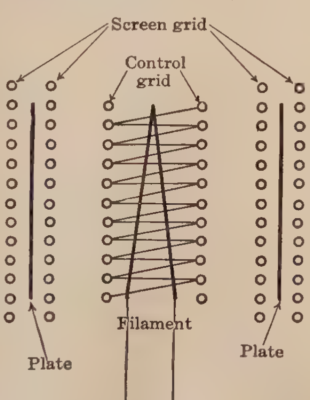

FIG. 92.—A cross-section showing the internal arrangement of the screen grid tube.

side the plate, as shown in Fig. 92. The two spirals are connected together and connected to the " screen grid " terminal of the tube. This is no longer a triode; it is called a four-electrode tube or **tetrode.**

The normal connection of the screen grid tube is shown in Fig. 93; the screen grid as shown there is connected to a suitable point on the B battery. Because of this connection its potential with respect to ground cannot appreciably vary and this prevents the electric field of the plate " reaching through " and affecting the control grid. The screen grid tube has a very high amplification constant and very high plate resistance, R_p. The latter, instead

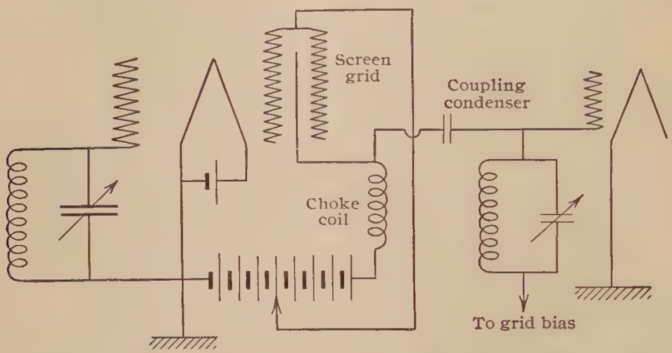

FIG. 93.—Circuit arrangement for utilizing the screen grid tube.

of being about 10,000 ohms as it is in the ordinary triode, is more like 500,000 ohms. Its characteristics make it somewhat difficult to design a suitable circuit to take advantage of its high amplification constant so it has not yet come into very general use.

32. Use of Alternating Current for Heating Filaments.—The ordinary triode uses about 0.25 ampere, at 5 volts, for heating its filament. Continuous current supply (a 6-volt storage battery) is required and of course, as this needs to be periodically charged, it would be advantageous if the filaments could be heated from the alternating-current power supply with which the ordinary house is equipped. If a 6-volt-alternating-current supply should be substituted for the 6-volt battery of the ordinary battery-operated receiver there would be a hum in the loud speaker so loud that any signal would be inaudible. Two vital changes were necessary before 60-cycle alternating-current supply could be substituted

for the storage battery. A low-voltage filament must be used and the " return " to the filament circuit must be made at a point electrically half way between the two filament terminals. Fig. 94 shows how this is done. A transformer *T* steps the 110-volt 60-cycle supply down to about 2 volts, for which voltage the filaments are designed. Across the filament circuit there is a resistance *R* and an adjustable contact *A* serves as the common connection of filament, grid and plate circuits. The adjustment of point *A* is carried out after the radio set is assembled; it is moved until

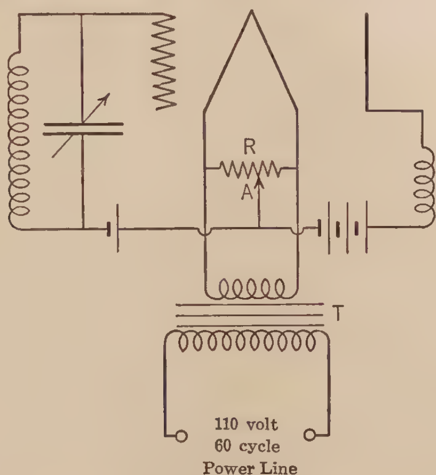

Fig. 94.—Circuit arrangement for using alternating current for heating the filament of the triode; correct positioning of the contact *A* in the potentiometer *R* is required to minimize the hum produced by the alternating current.

the hum in the loud speaker is a minimum. By the time this book comes from the press there will be practically no battery-operated sets being manufactured; the alternating-current filament triode is rapidly supplanting the battery-operated tube.

These alternating-current triodes require a certain bias to reduce the hum to a permissible amount and of course the plate circuit requires its continuous current supply. There would be but little advantage in dispensing with the filament battery and still requirig batteries for *C* bias and plate circuits. As will be shown in Chapter VII both grid bias and any desired continuous voltage for the plate circuit may also be obtained from the alternating-cur-

rent power line. Thus the triode has all of its circuits energized from one alternating-current transformer.

33. Use of Heater Tube for Detector.—Even though the filaments of the radio and audio-frequency amplifier tubes will operate satisfactorily with alternating current used for heating, the detector tube requires special arrangements. If it is attempted to use the 1-volt or 2-volt alternating-current filament, which serve reasonably well for the amplifiers, loud hum will occur in the loud speaker even after the ordinary precautions have been taken to eliminate it. A special triode has been designed to overcome this difficulty.

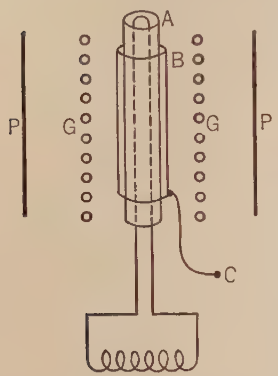

FIG. 95.—The internal construction of the "heater" type of tube, using alternating current for heating its filament. The cathode C need not be connected to the filament circuit at all; it is heated by the red-hot porcelain cylinder A.

In Fig. 95 the present-day alternating-current operated detector tube is indicated. The alternating current of about 0.25 ampere at 5 volts flows through a fine tungsten wire which is threaded through two longitudinal holes in a small cylinder of insulating material such as isolantite or porcelain. The two sides of this filament are very close together, the two holes in the insulation cylinder being about 0.05 inch apart. This results in a single turn coil of such narrow opening that the magnetic field set up by the filament current is practically negligible.

Tightly around the insulation cylinder is fastened a shorter cylindrical sleeve, made of a metal which emits electrons freely at low temperature. The filament heats up the insulation cylinder to dull red heat and this heats the sleeve sufficiently to produce the requisite electron emission. In Fig. 95 this hot cathode is indicated at B; there is a wire connecting to this cathode which comes out of the base of the tube as its cathode connection. Around this cathode are arranged the ordinary spiral grid G and plate P. In this heater tube the plate is generally made of fine mesh screen.

Evidently this form of tube requires five terminals, two for the filament, and one each for cathode, grid and plate. The filament circuit of this tube is entirely independent, electrically, of the grid

and plate circuits of the tube; the cathode terminal, C, forms the common return path for grid and plate circuits. The filament is a heater, pure and simple, and is in no fashion connected with the radio circuits. This five-terminal, heater type tube promises to find greater application than merely that of detector; it requires no balancing potentiometer as shown necessary for the alternating-current filament tube of Fig. 94.

It is evident that the filament must be much hotter than the cathode itself (because of the much greater surface of cathode compared to that of the filament) and this has caused some difficulty in obtaining a reasonable life of the filament. With increased knowledge of the factors shortening the life of the insulation-enclosed filament, the life of the filament is being lengthened and the utility of the tube correspondingly increased.

34. Constancy of Frequency of Current in Oscillating Triode Circuit.—As stated when analyzing the circuits of Figs. 85 and 86, the frequency of the oscillations which occur (after the tube has been set into oscillation) is fixed by the L and C of the circuit. This is not quite true because the resistances of the grid and plate circuits, as well as the amplification of the tube, have a slight effect on the frequency. It is evident, therefore, that any effect which influences these factors should affect the frequency of oscillation and such is found to be the fact. A change in either the filament current or plate voltage will produce variation in frequency, the variations sometimes amounting to 1 per cent, even without excessive changes in I_f and E_b.

However, if batteries are used for filament and plate circuits and the set has been operating for an hour or two to get the batteries in a " steady " condition, and to warm up coils and condensers as much as they are going to, the frequency stays remarkably constant. Thus in one such circuit the frequency of a 50-kc. power set in the laboratory varied less than 5 cycles a second in two hours. In a smaller, 100-kc. set, which gave practically no drain on the batteries and did not appreciably heat the apparatus, the change in frequency was about 1 cycle per second in half an hour.

35. Fixing Frequency by Piezo-Electric Crystal.—There are certain crystals, notably quartz and Rochelle salts, which show the phenomenon of piezo electricity, or development of electric charge as a result of pressure. A suitably crystallized piece of Rochelle salts will show a difference of potential on two of its faces as high

as several hundred volts, when vigorously twisted. A piece of quartz crystal, properly cut, will develop a few volts difference of potential between its opposite faces when squeezed. These crystals develop a charge when their shape is changed, and as the phenomenon is a reversible one, they change their shape when charged.

This peculiar action makes it possible to control the frequency of oscillation of a triode, by the mechanical vibration of a piece of quartz. Quartz is, mechanically, a very perfect material; it is perfectly elastic, having almost no loss due to viscosity, and is affected but little by temperature, etc. A piece of quartz, started into mechanical oscillation by a blow, will vibrate for a very long

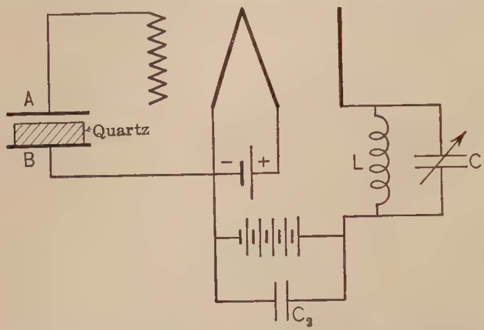

FIG. 96.—A common circuit for producing oscillations from the piezo-electrically active quartz disc; the frequency of the electrical oscillations is determined by the natural mechanical vibratory period of the quartz.

time, when compared to steel and other reasonably elastic materials. This means that quartz requires but little energy to maintain it in mechanical oscillation. Weather conditions and temperature have practically no effect on the elastic properties of quartz so that the natural period of a piece of quartz is nearly constant; certainly it is constant, under ordinary conditions, to a very small fraction of 1 per cent.

In Fig. 96 is shown a common arrangement of circuit, quartz, and triode, for obtaining a standard frequency oscillator. A small piece of quartz, perhaps as big as a dime, is loosely held between two metal plates A and B, forming a minute condenser. This piece of quartz will have a certain mechanical period of vibration, depending upon its thickness, and when the plate circuit is electrically tuned to approximately the same frequency as the mechanical frequency of the quartz the circuit will oscillate quite violently.

The tuning of the plate circuit is merely to facilitate the transfer of energy from the plate circuit (where the source of energy, the B battery, is located) to the grid circuit, not to set the frequency. There may be a considerable range of the variable condenser C which serves to sustain oscillations but it may be observed that as C is varied the frequency of oscillation does not vary at all. A small dry cell tube, with only 20 volts in the plate circuit, will operate this circuit if the quartz disc is good, piezo-electrically.

This scheme is much used nowadays for either checking, or setting, the frequency of a broadcasting station. In case it is used only for checking station frequency, the beat note between the station and the quartz oscillator is observed; the frequency of this beat note is kept close to zero, by adjusting the station circuit. In case the quartz oscillator is used for setting the station frequency it is arranged to actually excite the grids of the big power tubes, through a proper set of amplifying circuits; by exciting a 5-watt tube from the small oscillator, a 50-watt tube from the 5-watt tube, and then a 500-watt tube from the 50-watt tube, etc., the small quartz oscillator actually sets the frequency of the 5-kw. or 50-kw. power tubes of the station.

The quartz oscillator has recently been used for checking the frequency standards of the several countries interested in radio; by using the quartz oscillator at constant temperature, and using constant voltage in the filament and plate circuits, an oscillator may be transported from one country to another without changing its frequency by as much as 0.003 per cent.

Depending upon just how the plate is cut out of the quartz crystal, its thickness for a certain frequency of oscillation varies as much as 50 per cent; with the average crystal, and the disc cut out parallel to one of the faces of the crystal the wave length generated by the circuit is from 140 to 150 meters per millimeter thickness of the disc. If the disc is cut out of a slab which was cut out of the quartz crystal perpendicular to one of its faces the wave length generated is from 100 to 110 meters per millimeter thickness of disc. Thus with the first method of cutting, an 1800-kc. disc is 1.19 mm. thick. Its thickness must not vary from one part to another by more than about 0.001 mm. or else the disc will not set up oscillations in the triode circuit. This is because the different parts, of different thicknesses, will try to oscillate at different frequencies.

CHAPTER V

RADIO TELEGRAPHY

1. Code Used in Telegraphy.—Radio telegraphy is carried on by so operating the transmitting set that the receiving operator hears a series of dots and dashes. Various codes have been used, but the standard code today is known as Continental Morse. In this code a dash is equal in time to three dots; the interval between two elements of a letter is the length of a dot; the interval between letters in a word is equal in length to a dash, etc. A good operator can read well sent code at the rate of from 30 to 40 words a minute.

Various abbreviations are utilized for the expressions commonly used, such as "Wait," "Don't understand," etc. In the accompanying table are given the code signals for letters and numerals; the skilled operator must memorize a good many abbreviations as well as the signals given here:

A ._	B _...	C _._.	D _..
E .	F .._.	G __.	H ....
I ..	J .___	K _._	L ._..
M __	N _.	O ___	P .__.
Q __._	R ._.	S ...	T _
U .._	V ..._	W ___	X _.._
Y _.__	Z __.		
1 .____	2 ..___	3 ...__	4 ...._
5	6 _....	7 __...	8 ___..
9 ____.	0 _____		
Call _._._	Wait ._...	Don't understand _....._.	
Finish ._._.	Understand ..._.		

2. Types of Telegraph Waves: Spark and Continuous.—There are in general two types of radio waves used in radio telegraphy. In one, called **spark telegraphy** or **damped-wave telegraphy,** groups of high-frequency waves are sent off from the transmitting antenna as long as the sending key is held down. The

groups of waves follow one another in regular succession, generally about 1000 per second. In the receiving circuit each group of waves gives one impulse to the telephone diaphragm, so that the diaphragm receives 1000 pulls per second. This gives to the listening operator a musical note, of 1000 vibrations per second. The number of impulses received by the diaphragm for a single dot or dash depends upon how rapidly the transmitting operator is sending the message; in ordinary sending the dot lasts for about 100 impulses.

In **continuous-wave telegraphy** the transmitting antenna sends off high-frequency waves continuously, as long as the key is held down; the waves are not broken up into groups as they are in spark telegraphy. This type of signal requires special receiving apparatus; there is no action in the transmitter which permits the receiving operator to get a musical note. The note is obtained in the receiving set by producing interference, or "beats," between the received signal and a locally generated signal of nearly the same frequency as that being received. It is called the **heterodyne** method of reception. The continuous-wave scheme is evidently more complicated than the spark system, but it has the advantages that the operator can adjust the musical note in the telephone at will, and the receiver is more sensitive and selective than the spark receiver.

Spark telegraphy is being gradually replaced by the continuous-wave system; today the former is practically confined to the merchant marine. Naval vessels, the better class of merchant ships, large trans-oceanic stations, and practically all amateurs today use continuous waves for their telegraphic communication.

3. The Spark Transmitter.—The arrangement of apparatus in a simple spark transmitter is indicated in Fig. 97. A motor-driven alternating-current generator, G, generally of 500-cycle frequency, is connected through key, K, to primary of transformer, T. The transmitting key, K, may be hand-operated on small sets, but is generally magnetically operated, the operator using a small key which actuates the magnetic key. The transformer, T, steps up the voltage of the generator from 110 to about 20,000 volts. The capacity, C, is made up of mica condensers, or Leyden jars. On a 500-cycle set there are about 4 jars (each of 0.002 μf capacity) for each kilowatt rating of the transmitter. The operating voltage of the condenser is from 10,000 to 15,000 volts.

The combination L_1, L_2 is a pair of co-axial spiral coils; if the set is to radiate a 600-meter wave (general in the merchant marine) these coils will have from five to fifteen turns each, of about 10-inch average diameter. One of the coils is mounted so that it is movable in the direction of its axis; this adjustment serves to vary the magnetic coupling. This combination of coils is called the **oscillation transformer.**

Connected across the secondary of the transformer is the spark gap S. Many different types have been used in the past but today there are used only the **synchronous rotating gap** and the **quenched**

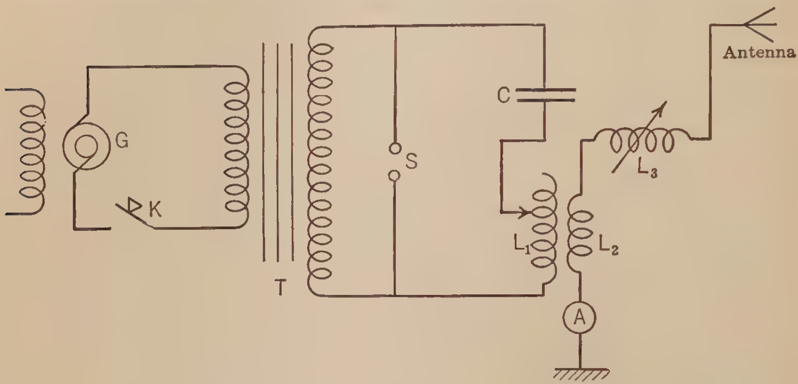

FIG. 97.—Simple circuit arrangement of a spark transmitter.

gap. The spark gap breaks down when the condenser is charged to the proper voltage; when broken down it offers a low resistance to the discharge of condenser C through the inductance L_1. This discharge is oscillatory, of frequency fixed by the inductance and capacity, that is, $f = \frac{1}{2\pi\sqrt{L_1C}}$.

The spark gap must not only offer low resistance to this oscillatory discharge, but after the oscillatory current ceases, must immediately recover its normal, high, insulation. It must accomplish this change from low resistance to practically an open circuit in about one-millionth of a second. This requirement accounts for the special forms of gaps mentioned above.

In Fig. 98 there is shown the construction of a synchronous rotating gap. The spark passes through two gaps in series, from each stationary stud to the opposing stud on the rotating disc.

Due to the fact that there are as many studs on the rotating disc as there are poles on the generator, this form of gap gives as many discharges per second as there are alternations in the generator

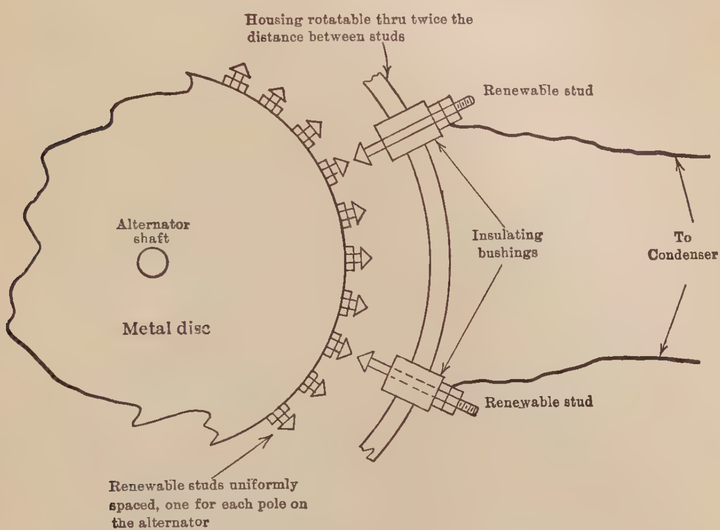

Fig. 98.—Arrangement of a synchronous rotating gap.

e.m.f. The fan action of the rotating disc serves to keep the studs cool, this being necessary if the gap is to restore its insulation in the very short time mentioned above.

In another form of spark gap, the **quenched gap**, the spark jumps through several short gaps in series. Each small gap is about 0.01 inch long, between the flat smooth faces of silver-coated copper discs, in a small air-tight chamber. The construction of such a gap is indicated in Fig. 99, which shows a cross-section of three discs and two sparking chambers. These chambers are made practically air-tight by the semi-elastic insulating gaskets, which are tightly compressed by the copper discs. In Fig. 100 is shown a view of an assembled quenching gap; and extra gap section is shown with the size of the sparking surface indicated, in

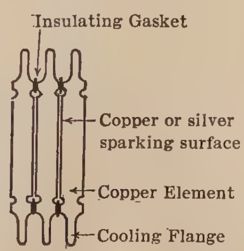

Fig. 99. — Cross-section view of two sections of a quenched spark gap.

dotted line. For a quenched gap to function properly two conditions must be fulfilled: the gap must remain air-tight, and the coupling between the two coils of the oscillation transformer must be reasonably close to its specified value.

Referring again to Fig. 97, the variable inductance L_3 is called the **loading coil** of the antenna. Its function is to tune the antenna circuit for the desired frequency. The ammeter A, of the hot wire or thermo-couple type, serves to show the amount of antenna current.

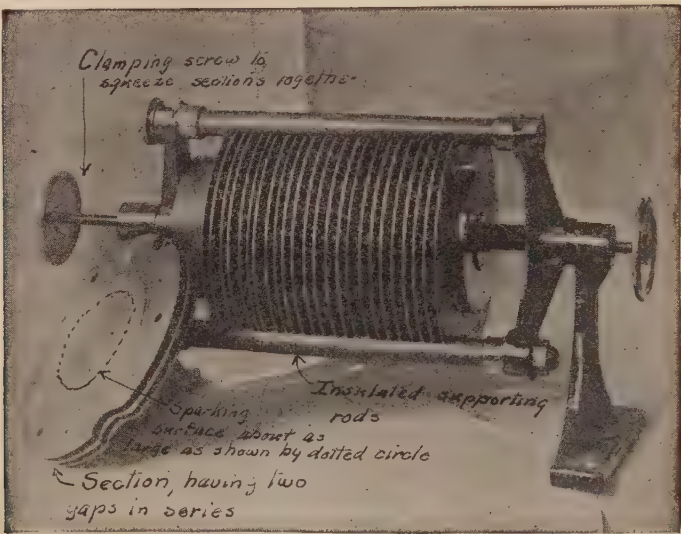

FIG. 100.—Appearance of a small quenched spark gap having about fifteen short gaps in series. Normally about ten of them are used, having altogether a break-down voltage of 10,000–15,000 volts

4. How the Spark Transmitter Works.—Referring again to Fig. 97 we will suppose the generator is revolving at proper speed, with proper excitation. When the key K is closed, the high voltage secondary of transformer T starts to charge condenser C, through inductance, L_1. When the condenser is charged to a certain voltage, depending upon the length of the spark gap, this breaks down and a current of hundreds of amperes rushes through the gap. This high current produces a hot " fat " spark, of low resistance. As the oscillatory current, of frequency equal to $\dfrac{1}{2\pi\sqrt{L_1C}}$,

flows through L_1 it induces a voltage in L_2, thus starting current in the antenna circuit; this circuit has been tuned to the L_1C circuit, by adjusting L_3.

As the current amplitude in the antenna (**the open oscillatory current**) increases that of the **closed oscillatory circuit,** L_1,C,S, diminishes, and in a few cycles is practically zero. At this time the gap should "open" or "quench," restoring its normal high resistance. The oscillatory current persists in the antenna for a length of time depending upon the frequency and decrement of the antenna circuit. The decrement (see p. 53) is equal to $R/2fL$, in which R is the total resistance, L is the total inductance of the antenna circuit, and f is the frequency of the current. For the average antenna the decrement is between 0.05 and 0.2. In the United States the value of 0.2 is fixed by law as the upper limit for the decrement of a ship's antenna.

When the amplitude of the oscillatory current in the antenna has decreased to 1 per cent of its maximum value the wave train is regarded as ended. The number of cycles of current in the antenna before the current decreases to this value is given by the relation

$$N = \frac{4.6 + \delta}{\delta}, \quad \ldots \ldots \quad (58)$$

in which δ is the antenna decrement. Thus an antenna with a decrement of 0.15 would have about 32 cycles before the current amplitude decreased to 1 per cent. Such a current would look about like that in the upper oscillagram of Fig. 101; the oscillatory current in the lower part of this illustration shows a current having a decrement of about 0.8.

When the generator, of Fig. 97, reverses its voltage and builds up in the opposite direction, the spark gap will again break down and there will be in the antenna another current of the form of Fig. 101. Thus for each alternation of the generator a wave train of radiation is sent off, each wave train being what is called a "damped sine wave." If the key K is held down for a dash of the telegraphic code (about 0.3 second) and the generator G is a 500-cycle machine there will be sent off from the antenna $0.3 \times 500 \times 2 = 300$ wave trains of electromagnetic waves, each train having the form of the upper curve of Fig. 101. The currents set up in the receiving antenna will be quite similar in form to the currents in the transmitting antenna.

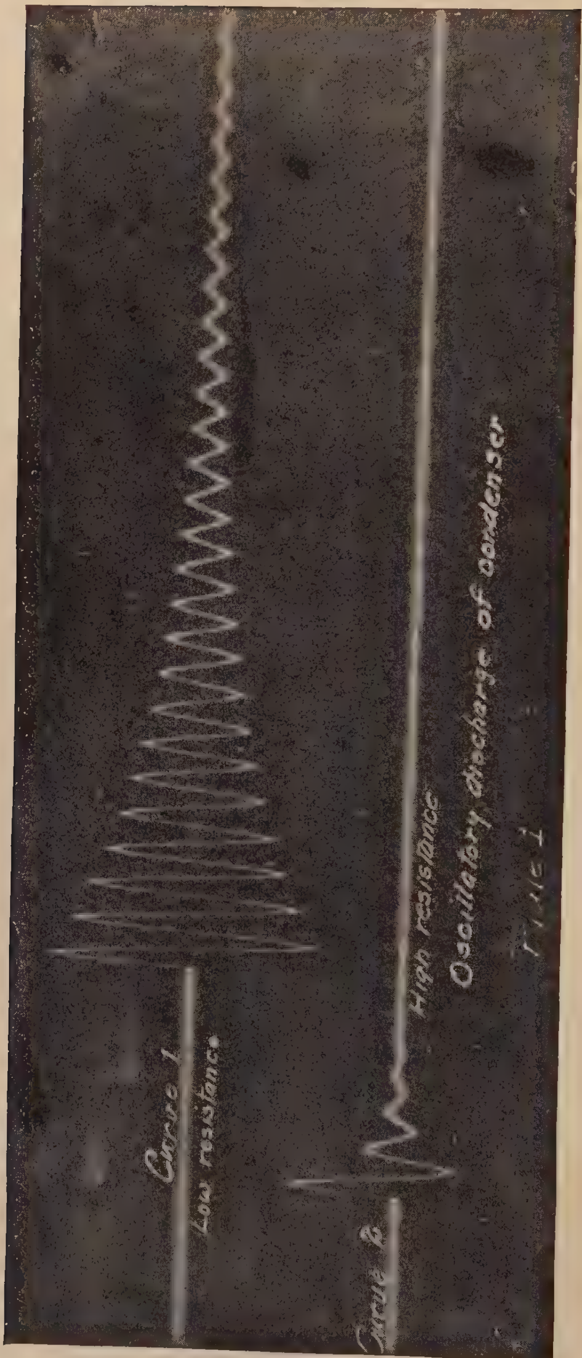

FIG. 101.—Curve 1 shows a damped sine wave with a decrement of about 0.2 and curve 2 has a decrement of about 0.8.

5. The Spark-Wave Receiver.—In Fig. 102 there is shown a simple receiving circuit for receiving spark-wave signals. The antenna A is connected to ground through the variable inductance L_1; this inductance, in conjunction with the antenna capacity, serves to tune the antenna circuit to the frequency of the signal it

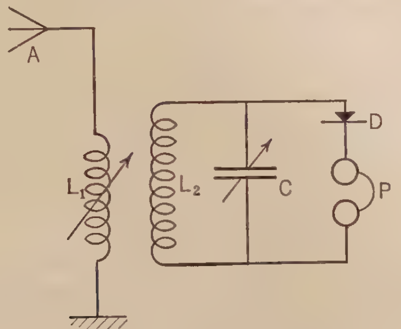

FIG. 102.—Receiving circuit using a crystal detector.

is desired to receive. The closed tuned circuit, L_2C, is also adjusted for resonance with the desired signal, that is, it is tuned to the antenna circuit. The coils L_1 and L_2 are loosely coupled, generally not more than 10 per cent.

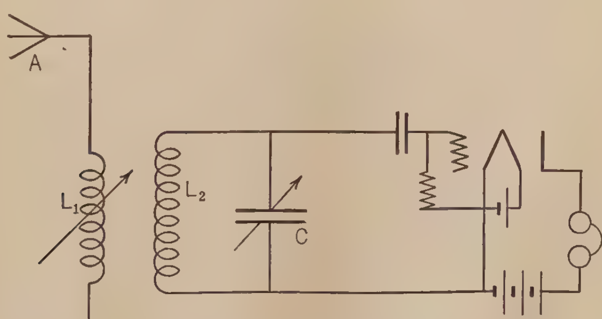

FIG. 103.—Receiving circuit using a triode as detector. (See also the legend of Fig. 113.)

Around the condenser C is connected the telephone receiver P, in series with the rectifying device D (generally a crystal contact). In case a triode is used as detector the circuits are connected as shown in Fig. 103. The function of the detector D of Fig. 102, and of the triode in Fig. 103, is to change the series of wave trains, of

high-frequency current, which are tuned in the L_2C circuit, into a series of pulses of current in the telephone, the number of pulses of current per second being equal to the number of wave trains per second. That is, the detector changes a wave train, such as that of Fig. 101, into one pulse of current in the telephone.

In "picking up" a signal the coupling of L_1 and L_2 is made reasonably tight, and both L_1 and C are varied, keeping them at the proper relative values to keep the circuits approximately in tune with each other. When the signal is found it is likely that other signals also will be heard in the phones, giving interference. To reduce the interference the coupling of L_1 and L_2 is weakened as L_1 and C are constantly varied to keep the desired signal at its maximum strength. As this procedure is continued it will be found that two results are attained. Interfering signals, of wave length differing from that of the desired signal, continually become weaker as the procedure is carried out; the desired signal increases in intensity for a time, as the coupling is weakened (the circuits being continually tested to maintain resonance with the desired signal) and then the signal falls off in strength. Maximum signal strength, with the ordinary crystal receiving set and spark signal of ordinary decrement will be obtained with from 10 to 20 per cent coupling of L_1 and L_2.

The "best coupling" will be weaker for the circuit using the triode detector than for that using the crystal detector.

6. Comparison of Crystal Rectifier and Triode.—Almost any contact, between dissimilar conductors, rectifies to some extent, but to serve as the rectifier D, of Fig. 102, only certain crystal contacts are suitable. A sharp steel point, pressing lightly on carborundum, galena, silicon, etc., has been much used in radio sets; the galena furnishes a much more sensitive detector than the others, but the sensitive spot is more easily "lost" due to a slight jar, heavy pulse of static, etc.

A good crystal detector should rectify well, i.e., give much more current when the signal voltage is in one direction than when in the other, should have a high resistance and should retain its sensitive condition in spite of mechanical jars, heavy signals, etc. In Fig. 104 is shown the characteristic curve of a rectifying contact between a needle point and a very good spot on a galena crystal. This curve is obtained by a continuous-current test; small adjustable voltages are impressed on the contact, in both directions, and

the corresponding current measured with a sensitive ammeter. It is evident that with 0.15 volt impressed the current is about six times as great in one direction as in the other.

If an alternating voltage is impressed on such a contact, and the current which flows is measured by a continuous-current meter (one of the type which does not indicate at all for alternating current) a direct indication of its rectifying properties is obtained.

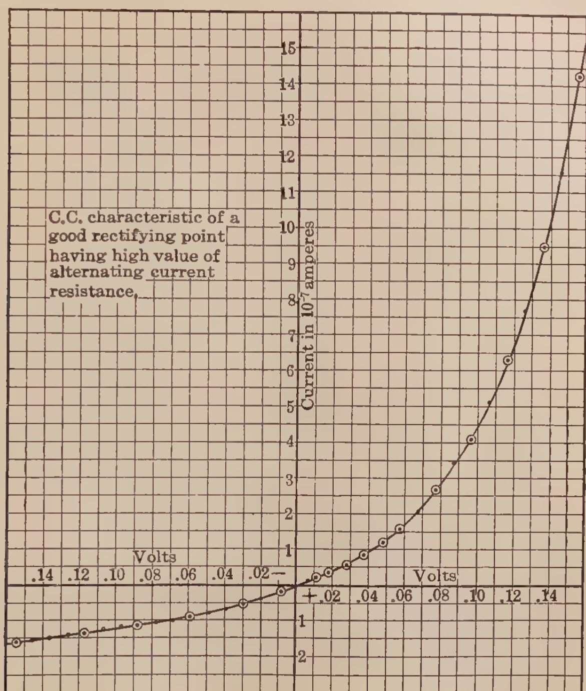

FIG. 104.—Current-voltage relation of a galena crystal detector; it rectifies well and has a high value of alternating current resistance.

In Fig. 105 are shown three curves obtained in this way. Curve *A* shows the rectifying property of a galena crystal and curves *B* and *C* show the action of a triode used as detector. Curve *B* shows the action of the triode when no grid condenser was used and curve *C* shows the action when suitable grid condenser and leak were used. Evidently the triode is more efficient than the crystal, especially when used with grid condenser and leak. The

triode has the further advantage that its rectifying properties are not spoiled by jarring or heavy signals. It has the disadvantage, however, of being more costly and requiring batteries for its operation.

7. The Telephone Receiver.—The ordinary telephone receiver consists essentially of a thin iron diaphragm, pulled inward at its center by two small magnetic poles which are very close to the diaphragm, these poles are energized by a small permanent magnet.

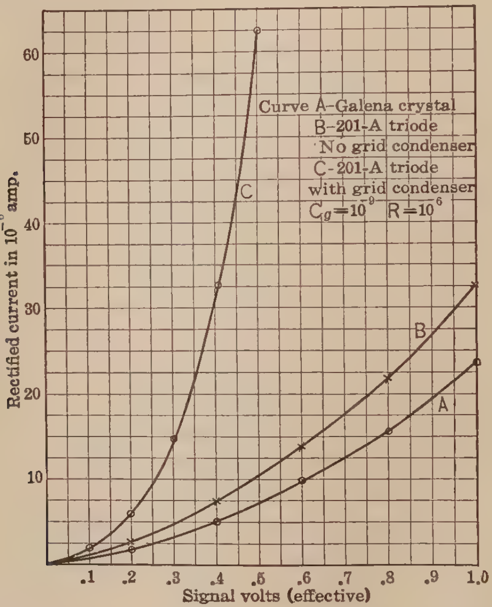

FIG. 105.—Showing the comparative rectifying ability of A, crystal; B, triode using plate rectification; C, triode using grid rectification.

Around the poles, which are of soft iron, many thousand turns of fine wire are wound; when current flows through these windings the pull on the diaphragm is increased or decreased, depending on the direction of the current. In one direction it assists the pull of the permanent magnet, and in the other direction it opposes the permanent magnet and thus diminishes the pull on the diaphragm. The general construction of such a telephone is indicated in Fig. 106.

In another type of telephone more sensitive than the foregoing,

a magnetically balanced iron armature is used, being so supported that it may rock; the construction is shown in Fig. 107. The armature is a thin iron reed, perhaps 0.03 inch thick, 0.20 inch wide and 0.75 inch long. The flux from the permanent magnet ordinarily goes directly through the armature, from the two south-pole pieces to the two north-pole pieces. But when there is current in the telephone winding the flux of the permanent magnet is urged

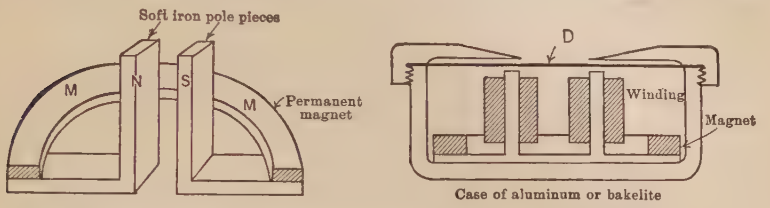

Fig. 106.—Approximate construction of the ordinary head phone.

to travel lengthwise through the armature, from one south pole to the diagonally opposite north pole. This redistribution of the flux results in a pull which rocks the armature, and as the tip of the armature is fastened to the center of the diaphragm by a short rigid rod, the diaphragm is forced to move in and out in accordance with the rocking motion of the armature. The diaphragm is, of

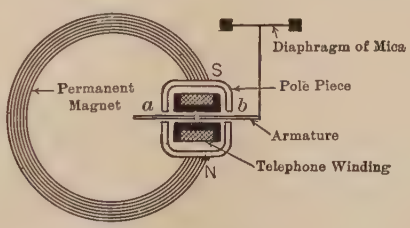

Fig. 107.—Construction of the balanced armature type of telephone; the diaphragm is of course proportionally much larger than shown here.

course, proportionately much larger than it is shown in Fig. 105, and the pole pieces are fitted to the permanent magnet in somewhat different fashion; the figure is merely to show how the various parts function.

This type of telephone receiver mechanism, in suitably enlarged form, has been much used for operating the paper cone of the ordinary cone loud speaker.

The resistance of the wire of the ordinary headphone in radio is about 1000 ohms and the impedance at 1000 cycles per second is about 10,000 ohms. At this frequency the power factor of a headphone is from 0.5 to 0.7. A well-built headphone will give an easily readable signal (for a 1000-cycle note) with a current of about one-tenth of a microampere; in a quiet room a current of 10^{-9} ampere gives an audible sound. This represents a power input to the telephone receiver of about 10^{-15} watt or a sound output of something less than 10^{-16} watt.

8. The Continuous-Wave Transmitter.—The transmitter for continuous-wave telegraphy is much simpler than the spark transmitter. A high-frequency generator of some kind is connected to the antenna (generally by mutual induction) and supplies the

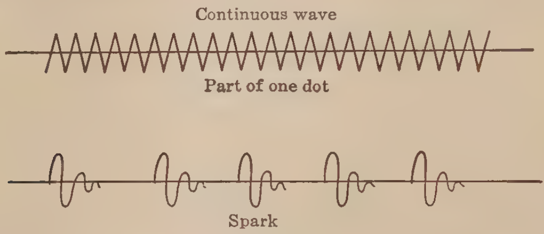

FIG. 108.—Forms of waves used in continuous, and spark-wave, telegraphy.

antenna with high-frequency current, of constant amplitude, as long as the key is depressed. The exact operation performed by the key depends upon the type of high-frequency generator used.

Thus if a wave length of 1000 meters is being used (300 kc.) a dot, one-tenth of a second long, would send out a continuous series of 300,000-cycle waves for one-tenth of a second. The dot would thus consist of 30,000 waves, all of the same amplitude. The difference between this type of telegraphy and spark telegraphy is conventionally illustrated in Fig. 108. The spark-wave dot, for a 500-cycle set, would consist of 100 wave trains, each train consisting of from 25 to 50 high-frequency waves, which are of rapidly diminishing amplitude, the last one being only 1 per cent of the amplitude of the first. The continuous wave dot consists of a high-frequency, constant-amplitude wave lasting for 0.1 second.

9. Types of Generators for Continuous-Wave Transmitters.—For the large trans-oceanic telegraph transmitters either an alternating current generator, or an oscillating arc, is used to excite

the antenna. In America the **inductor type of alternator** is used, in a form originally designed by Fessenden and perfected by Alexanderson. These generators are made in sizes as high as 200 kw., to generate directly frequencies between 20 and 30 kc. In Fig. 109 are shown several views of an Alexanderson alternator such as is used for trans-Atlantic telegraphy. In this type of transmitter the operator's key controls the field strength, generally through a train of relay keys.

To get an appreciable power from these high-frequency alternators the antenna circuit, as well as the generator circuit, must be accurately tuned to the generator frequency. If the antenna circuit is mistuned it takes from the generator only a small fraction of its normal power; taking advantage of this fact one method of transmitting has the antenna normally mistuned; when the operator closes his key the antenna is tuned to the generator (by changing its loading inductance) and thus draws power and radiates a signal.

Fig. 109.—Showing the construction and installation arrangement of a high-frequency alternator such as is used in trans-Oceanic telegraphy.

Most of our high-powered naval radio stations use a special form of arc (called a **Poulsen arc**) to furnish the high-frequency power to the antenna. A continuous current generator, of 750 to 1000 volts rating, is connected through a high inductance to an arc having carbon for one electrode, and water-cooled copper for the

other. The arc burns in a hydrogen, or illuminating gas, atmosphere and is situated in a transverse magnetic field of suitable intensity. One side of the arc is connected to ground and the other side to the antenna loading coil. Such an arrangement will set up an alternating current in the antenna, its frequency being the resonant frequency of the antenna circuit. The carbon electrode must be slowly rotated, otherwise the arc length varies and the antenna current shows corresponding variations.

Arc generators are most efficiently used at the longer wave lengths and are therefore usually operated above 5000 meters, and as high as 18,000 meters. The capacities range from a few kilowatts to 1000 kw.; the ordinary arc station is of about 350 kw. rating. In Fig. 110 is shown a simplified diagram of the arc circuit,

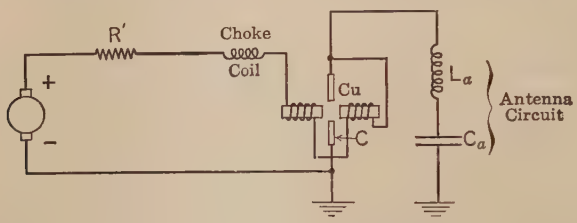

FIG. 110.—Simplified circuit arrangement of an arc transmitter.

L_a being the loading coil of the antenna and C_a the capacity of the antenna. In Fig. 111 is shown a view of a completely assembled Poulsen arc of 500 kw. rating. The arc chamber is directly under the top yoke of the magnet frame; the large pipe going from the arc chamber into the floor is to carry off the exhaust gas. The cylindrical structure under the arc chamber is the magnet winding; the tip of the magnet pole extends into the arc chamber, giving a vertically directed magnetic field, in which the horizontal arc burns. About 300 kw. is wasted as heat in this arc generator, so all parts have to be water-jacketed and cooled by circulating water.

It takes an appreciable time to start an arc generator and get it operating steadily; it would therefore evidently be impossible to start and stop the arc oscillations for sending the dots and dashes of the telegraph code. The usual method of sending permits the arc to generate full power all the time; the dots and dashes are sent by slightly changing the frequency being sent out from the antenna. This change in wave length is brought about by the operator's

key short-circuiting one turn of the antenna loading coil. The actual short-circuiting is done by a magnetically operated switch, the operator's key serving to energize this magnetic relay.

Arc generators send out not only the frequency for which their circuits are designed but many harmonics of this frequency. Thus a sensitive heterodyne receiver, adjusted to receive a frequency

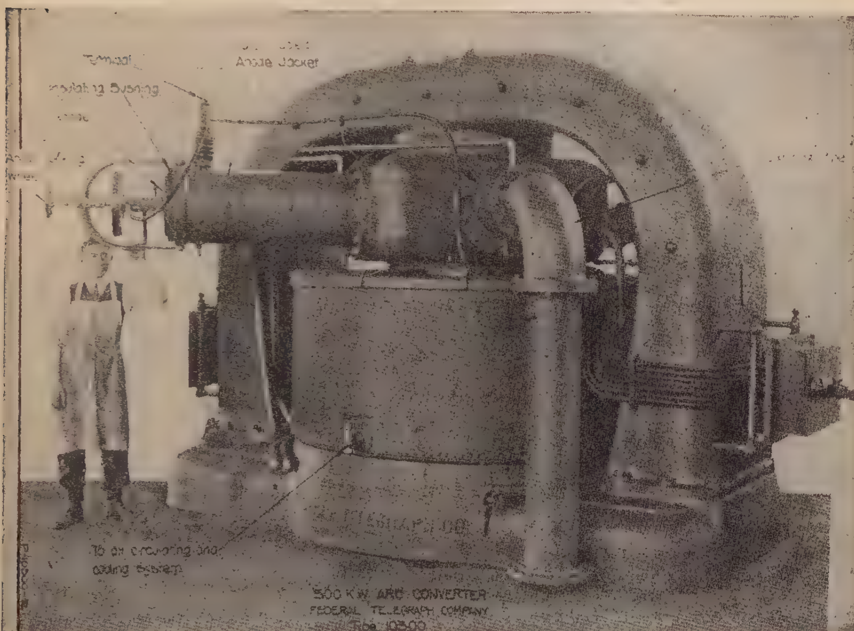

Fig. 111.—View of a 500-kw. Poulsen arc; over the operator's head is the anode terminal and on the right is shown the pipe for carrying off the exhaust gases from the arc chamber. (Proc. I.R.E., Vol. 7, No. 5.)

of 1100 kc., may hear the signal sent out by a 100-kc. arc station. The receiver is picking up the 11th harmonic of the arc.

The **oscillating triode** is of course another type of generator suitable for furnishing power for continuous-wave telegraphy. For the short waves, 100 meters and less, this type of generator is the *only one available.* There is no device, other than a triode or similarly acting tube, which will generate frequencies of 3000 kc. and more, as is demanded by short-wave telegraphy. In time the triode will undoubtedly displace both the Alexanderson alter-

nator and the Poulsen arc, for continuous wave transmitting purposes.

10. Transmitter for Interrupted Continuous-wave Telegraphy.—From what has been said before it is evident that the frequency of radio currents is much too high for the human ear to detect. In spark telegraphy the detector is really a frequency changer; the radio frequency currents come in groups and the detector enables the telephone receiver to respond to the *group frequency.* Now a continuous-wave signal has no group frequency of itself; the amplitude of the radio frequency current is constant.

If, however, the amplitude of the radio-frequency current is made to vary, at an audible frequency, then the detector will produce fluctuations in the telephone current corresponding to these variations in amplitude and hence yield an audible note.

It is perfectly possible for the continuous-wave transmitter to send off the radio frequency in groups, of say 500 per second. Then the system acts practically as a spark-wave system and a spark-wave receiver will act just the same as though the transmitter used the spark system. The triode oscillator will produce continuous waves of this type if the power supply in the plate circuit is a 500-cycle alternator. The triode will oscillate, and so produce radio-frequency power, only when the plate is positive; hence in the negative alternation of the alternator no oscillations are produced. Fig. 112 shows one embodiment of this scheme. The triode is arranged to oscillate, the plate circuit L_1C forming the oscillatory circuit; the feed-back from plate to grid is given by the magnetic coupling between L_1 and L_2. The coil L_3 couples the antenna to the oscillating circuit; either L_3 or some other coil in the antenna circuit must be variable so that the antenna may be tuned to the frequency desired.

The key, K, serves for signaling; when the key is open the grid (of a high-vacuum tube) will go highly negative, cut off the plate current, and so stop the oscillations. Such a scheme is not generally advisable, as it leaves a " floating " grid and this is permissible only in a thoroughly evacuated tube. A battery of small dry cells, poled negative to the grid, in series with a resistance of about 10,000 ohms, may be connected from grid to filament, between points A–B of Fig. 112. Such a scheme will force the grid to go negative, when the key is open, by an amount equal to the voltage of the battery; with the key closed the battery would be short-

circuited but the high series resistance keeps the discharge current to a low, permissible value.

Instead of using a B battery, or continuous current generator, in the plate circuit, an alternator G is used, shunted by a by-pass condenser C. The triode oscillates only when the generator makes the plate positive, so that there are radiated from the antenna as

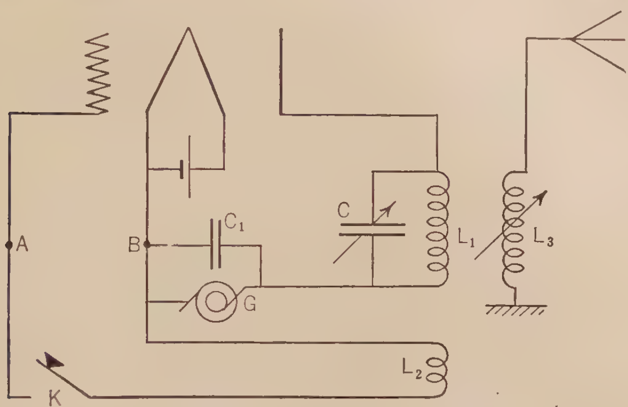

FIG. 112.—A simple triode circuit for sending out continuous-wave telegraph signals.

many groups of radio-frequency waves per second as there are cycles per second of the alternator.

11. The Heterodyne, or Beat, Receiver.—If the continuous-wave signal coming into the receiving circuit is of constant amplitude, some kind of amplitude variation must be produced in the receiver before the signal becomes audible. This requisite amplitude variation is obtained by using an oscillating triode for the detector, and so adjusting the locally generated radio-frequency current that the difference in frequency between this and the incoming signal is in the audible range. The triode oscillator and detector is arranged as in Fig. 113. The tickler coil in the plate circuit sets up oscillations in the circuit of L_1–L_2–C, the frequency of which is controlled by the variable condenser. Signal current is also set up in this circuit by its coupling to the antenna, so the grid voltage is due to the combination of these two high-frequency currents. In Fig. 114 the various voltages and currents are indicated; it can be seen that the telephone current (mean plate current) has a variation in amplitude of the same frequency as the

"beats" in the "resultant high-frequency current," and this is why it is called the beat receiver. The note heard in the telephone is entirely under the control of the operator; by changing the setting of the variable condenser only one or two divisions the note may be changed through the whole audible range. A small vernier condenser, in parallel with the main tuning condenser, is advisable in this type of receiver to facilitate the note-frequency adjustment. The vernier condenser is merely a small variable condenser (of capacity perhaps 5 per cent that of the main tuning condenser) placed in parallel with the main tuning condenser.

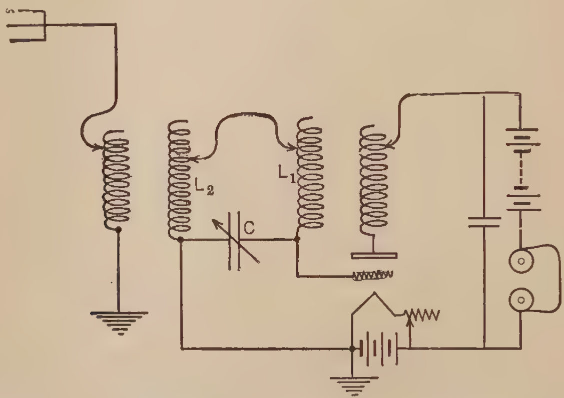

FIG. 113.—An oscillatory triode circuit for receiving continuous-wave signals; it is called the heterodyne, or beat, receiver. The regenerative circuit is also used for spark signal reception, but in this case the tickler coupling must be kept at a value less than that required to produce oscillations. The regenerative triode is many times as sensitive as one not utilizing regeneration.

The use of such a vernier condenser makes it easy to vary the capacity of the tuned circuit by very small amounts. The "rough" tuning is done by the main condenser and the "fine" tuning by the vernier.

12. Comparison of Spark and Continuous-wave Telegraphy.—For unskilled operators spark telegraphy is much more reliable than the continuous-wave system. If the receiving circuit stops oscillating and the operator is not keen enough to notice it, no signal can possibly be received from a continuous-wave transmitter. The operator must be continually on the alert to see that his receiver is oscillating. And it is to be remembered (p. 143) that with conditions right for oscillations with one value of tuning con-

denser, setting the condenser for a larger value is quite likely to stop the oscillations. Thus with the tickler coil having a certain adjustment the receiving circuit may oscillate with any setting of

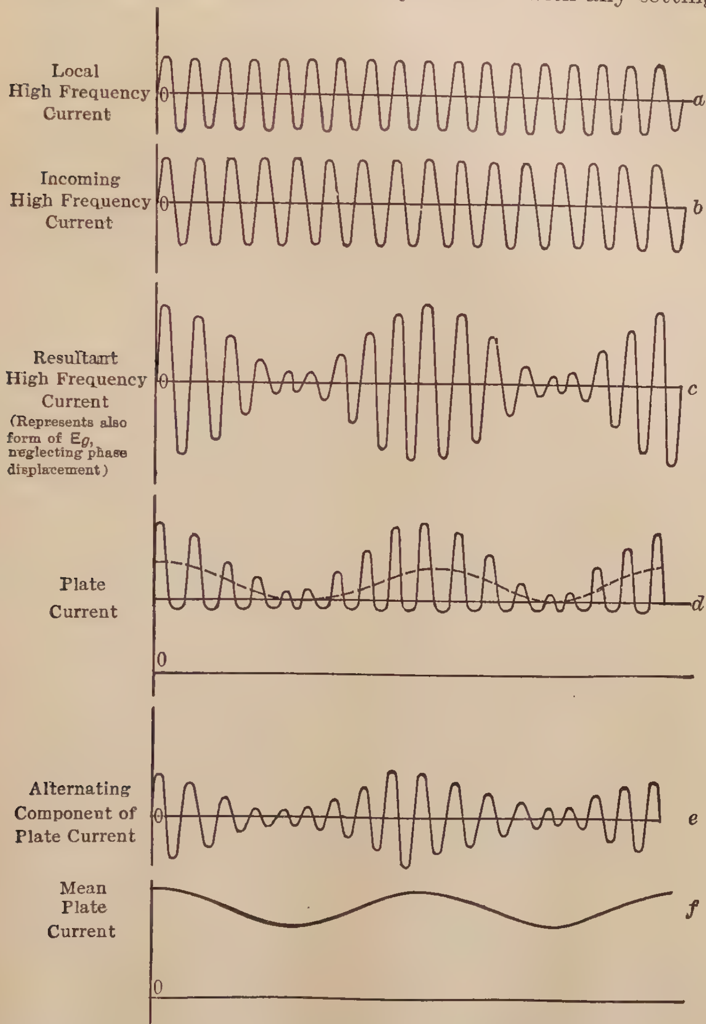

FIG. 114.—A series of curves to show the action of the heterodyne receiver.

the tuning condenser between 0 and 50 divisions and cease oscillating for larger values of capacity. Then as the operator turns the tuning condenser, looking for signals, he cannot possibly pick up

a signal between 50 and 100 dial divisions of the condenser, as there is no possibility of a beat note in this range.

Except for this one possible disadvantage the continuous-wave system is much superior to the spark system. The selectivity of the receiving set is much better, the operator can adjust the pitch of the signal to any note he likes and the beat receiver is very much more sensitive than the spark receiver. Accurate analysis shows that for a triode detector receiving a spark signal the telephone current (which gives the audible signal) decreases with the *square of the signal strength* (see Fig. 105) whereas if the same triode is being used as a beat receiver for a continuous-wave signal, the telephone current decreases with the *first power of the signal strength.* Thus as the signal becomes weak the response of the spark receiver approaches inaudibility much faster than is the case for the beat receiver.

Because of its several points of superiority the continuous-wave system has displaced spark telegraphy in all services except the merchant marine and here also it is coming to the front. For short-wave telegraphy, now being developed so rapidly, continuous waves are always used.

13. Amounts of Power Used.—The ordinary spark set on board ship has a 2 kw. rating; the high-frequency power supplied to the antenna may be about one kilowatt or less. In the night time, in winter, such a set may carry on communication over a thousand miles, but on a summer day it is good for only a hundred miles or so. In the semi-tropical regions, as the Gulf of Mexico, it may not furnish reliable communication for even 50 miles. This is primarily due to the heavy atmospheric disturbances. For trans-Atlantic telegraphy one or two hundred kilowatts are used and even then some " repeats " are necessary. In the more recent short-wave transmissions, a few kilowatts of power sometimes serve for communication half way around the world.

The present development of " point-to-point " telegraphy utilizes a directive antenna, acting much like a parabolic mirror, at both transmitter and receiver. For a given reliability of communication this mirror scheme is said to reduce the required power to only a few per cent of what would be required if ordinary antennas were used at both transmitter and receiver. This so-called " beam system " apparently permits commercially successful telegraphy, for thousands of miles, with only a few kilowatts of

power, using wave lengths of less than 50 meters. The mirror system can be used only with very short waves, because the size of mirror increases directly with the wave length. The mirror consists of a series of free antennas, arranged in certain fashion around the excited antenna. The currents set up in them act in conjunction with the excited antenna, to send out radiation along a rather narrow beam perhaps 30° wide. At the receiving end a similar set of antennas is used, the receiving apparatus being coupled to that antenna corresponding to the excited antenna at the transmitting station.

CHAPTER VI

RADIO TELEPHONY

1. Frequencies Used in Music and Speech.—Sound is a wave action which utilizes the air or some other elastic substance for its medium of travel. Radio waves travel even better in vacuum than in air, but sound waves are entirely impossible in a vacuum. Sound is a wave motion made up of successive compression zones and rarefaction zones following one another. In the case of "noise" the waves are not regular and periodic in their occurrence, but waves which give one the quality of pitch, or tone, are regular in their occurrence, and they follow one another in sufficiently rapid sequence. To be interpreted as a musical tone by the average listener there must be at least 50 complete waves per second. A complete wave consists of one zone of compression and one of rarefaction. A young child can hear a note when the frequency is as high as 20,000 waves a second but in older people the upper threshold of hearing is much lower. Many people in middle age cannot hear a note as high as 10,000 vibrations per second, no matter how loudly it is sounded.

It must not be thought that the waves of compression and rarefaction represent any great variation from the normal air pressure. Thus normal air pressure is about 14.7 lb. per sq. in. In the range of voice frequencies, a sound of average intensity, such as the speaking voice of a person a few feet away, would consist of zones of increased and decreased air pressure of about 0.000001 lb. per sq. in. Thus in the pressure zone the air pressure would be 14.700001 lb. per sq. in. and in the following rarefaction zone the pressure would be 14.699999 lb. per sq. in.

The pressure of the voice waves varies greatly with the modulation of the voice, and even in the interval of one word may vary 100 to 1 as the voice formulates consonants or vowels. A brief summary of the principal characteristics of the voice shows that:

(*a*) The frequencies encountered in human speech are within the range of 100 to 6000 complete vibrations per second.

(*b*) The energy contained in speech is carried almost completely by frequencies below 500 but the quality and intelligibility of speech is determined mostly by the frequencies above 500

(*c*) The average power output of the average normal voice is about 75 ergs per second, or 7.5 microwatts.

(*d*) The average male voice exerts a pressure of about 10 dynes per sq. cm. at a distance of 3 cm. from the mouth of the speaker. (One dyne per sq. cm. is about 0.00001 lb. per sq. in.)

(*e*) The human ear can detect sounds, at a frequency of about 1000 cycles, if the sound pressure is as low as 0.001 dyne per sq. cm. If the pressure exceeds about 1000 dynes per sq. cm. at this frequency the ear is practically paralyzed in so far as sound is concerned and the sensation is one of feeling rather than hearing.

(*f*) The ratio of peak power in the voice (accented syllable) to average is about 200 to 1. Thus an average voice of 10 microwatts power shows peaks, at the accented syllables, of 2000 microwatts.

2. Distribution of Energy in Speech.—Naturally any statements as to power of the voice, distribution of energy, etc., must be considered as qualitative, and average, only. Two people, using

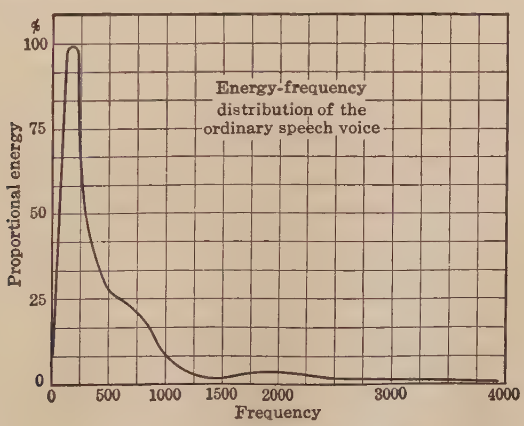

FIG. 115.—Distribution of energy of the average speaking voice.

normal voice, may show a ratio of 10 to 1 in the power they use, and, of course, in general the male voice contains more energy than the female. And, of course, the distribution of the energy in the various frequencies of the voice varies greatly with the quality of

voice. The consonants utilize the very high frequencies and, as casual observation shows, many people " slide over " the consonants while others pronounce them clearly.

In Fig. 115 is shown the energy distribution curve obtained as the average of 24 voices, male and female. It is clear that practically all of the " body " of the voice is made up of frequencies lower than 500 vibrations a second. In Fig. 116 is shown the response of the average ear, for the various frequencies. It is seen at once that the ear is most sensitive for those frequencies having but little of the voice energy. However the next section justifies such a frequency response for the ear.

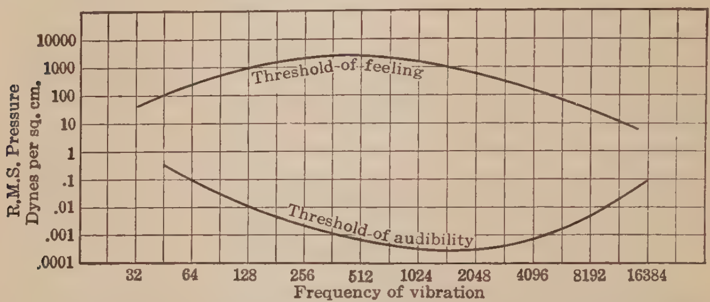

Fig. 116.—Showing how the action of the ear varies throughout the audible frequency range.

3. What Determines Intelligibility of Speech.—By means of suitable apparatus it is possible to change voice waves into alternating electric currents, the frequency and form of which correspond exactly to the frequency and form of the pressure waves of sound. By means of so-called " filters " it is possible to eliminate all of the frequencies in the electric current above a given value; this modified current can then be reconverted into sound and this sound will differ from the original in that certain high frequencies have been eliminated.

This distorted form of voice wave has been tested by the telephone engineers for its intelligibility, and so they have been enabled to tell just what frequencies in the voice are required for clarity of speech. In Fig. 117 the results of their investigations are given, and by comparing this curve with that of Fig. 115 it is seen that only a very small percentage of the energy of the voice contributes to intelligible expression; just what the function of the major part

of the energy in the lower frequencies may be is yet to be determined. We know that it contributes to the "naturalness" of the voice but that seems to be its only service.

4. The Microphone and its Action.—The microphones used in radio today are generally of the carbon granule type; these microphones may use single or double cells of carbon granules the latter being used almost exclusively in broadcasting stations.

The single-cell microphone has essentially the construction indicated in Fig. 118. It consists of an elastic diaphragm A mounted upon the rubber ring FF, which in turn is held against E, the diaphragm being mechanically connected to the carbon block

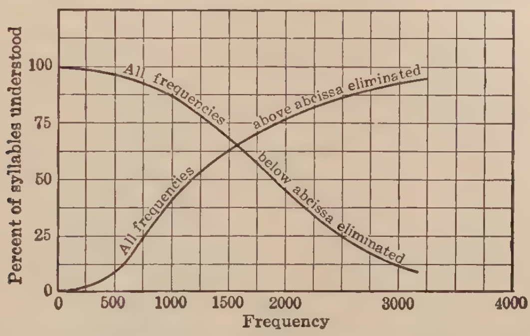

FIG. 117.—The intelligibility of the voice depends almost entirely upon the higher frequencies; if all of the energy below 500 cycles is eliminated the speech is still 90 per cent intelligible, although most of the energy has been taken away.

B'; B' is placed opposite another carbon block B in a chamber filled with small carbon granules C; this chamber is closed by means of the mica washer G and the insulating nut H. The two carbon blocks B and B' form the two electrical terminals of the transmitter; the wall of the chamber containing the granules is covered with a strip of paper shown at D.

If a source of e.m.f. is connected to B and B' it will send current from plate B, through the granules, to B', or vice versa. On speaking into the transmitter the diaphragm is caused to vibrate and these vibrations are mechanically transferred to the block B' so that the latter's pressure on the carbon granules is made to vary; this varies the resistance between B and B' and hence it also varies the current in the circuit wherein the transmitter is connected.

Such an arrangement is very sensitive to changes of pressure

on the diaphragm; it is known as a *microphone transmitter*. The current carried by such a transmitter is very small because of the fact that a limit is soon reached where minute arcs are developed between the granules, the contact points of which become very hot and the transmitter becomes useless. The current-carrying capacity of an ordinary transmitter is about 0.1 ampere and the average resistance when not spoken into is from 50 to 100 ohms, so that the power used in the granule chamber is about 1 watt.

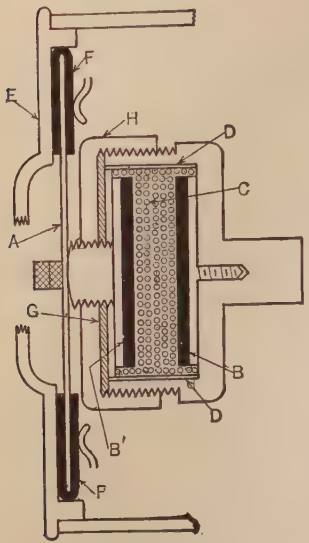

FIG. 118.—This diagram shows the internal construction of the ordinary carbon transmitter or microphone.

The maximum motion of the diaphragm of the ordinary microphone should not exceed 0.0001 in.; otherwise the alternating current output of the circuit will not resemble the sound pressure of the input. Thus if the sound pressure is a pure sine wave the fluctuation of current through the microphone will also be of sine wave form if the to-and-fro motion does not exceed the value given; if this is very much exceeded the current wave will depart from its sine form, being distorted by the presence of both even and odd harmonies. The distortion

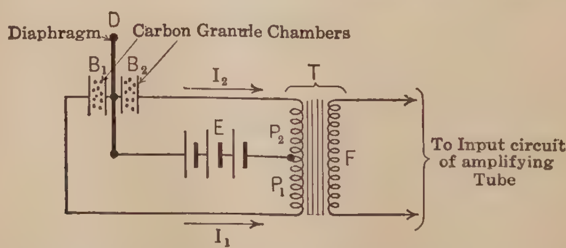

FIG. 119.—The double-button microphone eliminates some of the distortion occurring in the single microphone circuit, and, as made, gives a more uniform response for the various voice frequencies.

becomes increasingly greater as the sound pressure increases in intensity.

5. The Double-button Microphone.—By using two cells of carbon granules and making connections as shown in Fig. 119 some of the defects of the single-cell microphone are done away with. As shown in Fig. 119 this microphone consists of a diaphragm stretched between the two chambers containing the carbon granules. Evidently a sound wave which increases the pressure in one chamber will decrease it in the other, so that the current in one side decreases as that in the other increases. This idea of combining an increasing effect with a corresponding decreasing effect has been much used in radio; it goes by the name "push-pull." By using such apparatus the distortions due to *even harmonies* are eliminated.

To utilize the effect of the double-cell microphone a special transformer must be used, having a split primary. It will be seen by following the directions of windings and current that the opposing effects in the two cells do not balance out, but add together in the transformer. Thus the voltage induced in the secondary winding is twice as much as would be given by only one side of the microphone and is much more free from distortion than the single-cell microphone would be. Furthermore the steady value of current flowing through the microphone does not magnetize the core of the transformer at all; the magnetizing effects of the two halves of the primary winding just neutralize one another. It is only the *change in currents* I_1 *and* I_2 that produces flux in the core and hence voltage in the secondary coil.

It will furthermore be noticed that change in voltage of the battery has but little effect on the secondary voltage; such a change effects both I_1 and I_2 equally, so the circuit remains balanced whatever E may become.

The diaphragm is very tightly stretched, and placed a very short distance from a flat metal plate. The stretching makes the natural period very high and placing the diaphragm close to the metal plate gives a high damping effect. Both of these features of construction reduce the sensitiveness of the microphone so that more amplification must be used and, of course, amplification itself brings in some distortion.

The engineer has to balance these two effects. His knowledge of the characteristics of an amplifier is such that it pays to make the microphone very insensitive with the accompanying features of faithful reproduction. The microphone in general use in broad-

casting stations is but a small fraction as sensitive as the one used in common telephone circuits.

The microphone for use in radio transmitting circuits is always hung upon a spring suspension, so that floor and other vibrations do not disturb it. As ordinarily used this type of microphone gives in the secondary of the transformer about 5 millivolts for a sound-wave pressure of 1 dyne per sq. cm.; this is the pressure produced by the speaking voice about 6 in. from the mouth.

6. The Condenser Microphone.—This is probably the most perfect microphone used in telephony today but it is somewhat troublesome to maintain. Its construction and method of use are

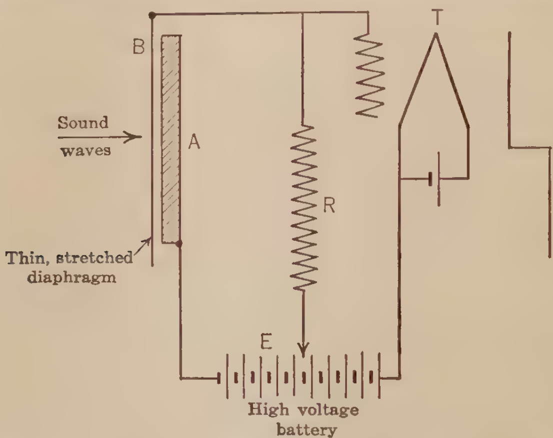

FIG. 120.—The condenser transmitter permits of very faithful voice reproduction, but is more difficult to maintain than the carbon-granule type.

illustrated simply in Fig. 120. Close to a heavy steel plate A is mounted a very thin, tightly stretched steel diaphragm B. As B is well insulated from A the pair form a small condenser with air for dielectric. The capacity of the condenser is small, being measured in a few micro-microfarads. A battery, E of several hundred volts in series with a high resistance R serves to charge the condenser. The drop across R is impressed on the input circuit of a triode, the normal drop (no sound actuating the microphone) on R being balanced out of the input circuit by the biasing battery C. As sound vibrations, acting on the thin plate B, push this back and forth, the distance between the plates of the condenser is correspondingly changed, its capacity is changed, and

hence pulsations of current occur in the charging circuit of the condenser. Thus the RI drop in the high resistance R follows the fluctuations in sound pressure on B and this drop actuates the triode T. This triode is a small one using dry cells for its operation and is placed right in the microphone mounting. This triode is the first one of a series of cascaded ones, constituting the *speech amplifier* of the radio station. As ordinarily installed this type of microphone gives about 0.3 millivolt on the input circuit of the triode, for a sound pressure of 1 dyne per sq. cm.

7. A Voice-modulated Wave.—As we have said before the voice consists of a vast number of frequencies, but for the first

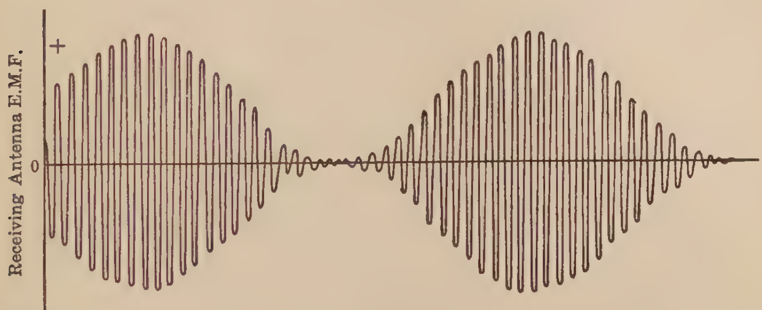

FIG. 121.—A high-frequency wave having sine wave modulation; such variation in amplitude as shown here is said to be 100% modulation.

analysis we attempt it is assumed that the voice is a pure sine wave. By a *voice-modulated high-frequency wave* is meant one of which the amplitude is varying according to the sound pressure of the voice, and if we assume this to be a simple sine curve then the modulated wave is one the amplitude of which follows a sine curve. Such a wave is shown in Fig. 121; the wave itself is high frequency and its amplitude increases and decreases according to some sine curve. The modulation frequency (frequency of amplitude fluctuations) is generally very low compared with the frequency of the wave itself; thus the wave itself may have a frequency of one million per second and the modulation frequency be 500 per second

The degree of modulation is determined by the variation of the amplitude of the radio frequency current from its unmodulated, or average, value. The wave of Fig. 121 is *completely modulated* because its minimum amplitude is zero; such a wave is said to be modulated 100 per cent. It is not good practice to modulate the

wave of a broadcast transmitting station too much; about 60 per cent modulation is as great as is used in the better class of station. The range of a broadcasting station increases, however, as the percentage of modulation is increased, so that a station trying to serve a wide territory, without regard to the quality of its signal, modulates up to the 100 per cent limit.

8. Composition of a Modulated Wave.—Let us suppose that the wave shown in Fig. 121 has a frequency of 500 kc. and that the frequency of modulation is 5 kc.; this would be a 600-meter wave, modulated by a very high musical note. It might then be reasonably thought that the modulated wave was a double one, having some power at 500 kc. and some power at 5 kc., but such is not the fact. Suppose the current shown in Fig. 121 is flowing through the

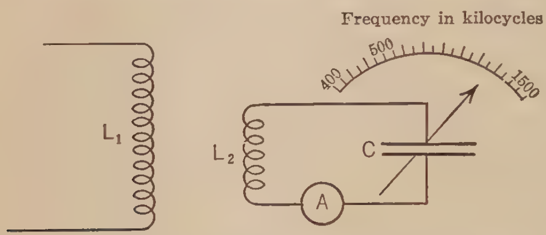

FIG. 122.—Connection of a frequency meter for investigating the form of current flowing in coil L_1.

coil L_1 of Fig. 122; coupled to L_1 is a resonant circuit consisting of the coil L_2, the variable condenser C, and the current indicating meter A. Such a device, when properly calibrated, is a *wave meter*, or *frequency meter*. If the frequency of the current in L_1 is maintained constant, and the capacity of C is varied, the current in the circuit, indicated by A, will rise to a high value when the L_2C circuit is in resonance with the frequency of the current in L_1.

Thus to find the frequency of the current in L_1 it is only necessary to vary C in small steps, read the meter A, and the frequency of the L_2C circuit for each setting of C. A curve is then constructed, with frequencies as abscissas and readings of A as ordinates. The curve which would be obtained in this fashion, with the apparatus as in Fig. 122, is shown in Fig. 123. There are one high resonance peak at 500 kc., and two others not so high, one at 495 kc. and one at 505 kc. If the frequency meter is adjusted for all other frequencies no other resonance peaks are found. We are

thus forced to the conclusion that the modulated current of Fig. 121 really consists of *three different currents,* one having the frequency of the unmodulated wave and two others, one higher than this unmodulated wave and one lower. And *the frequency separation between each of these two and the unmodulated frequency is the frequency of modulation.* The unmodulated frequency current is called the *carrier current* and the other two are called the *side bands.* In Fig. 123 the 500-kc. current is the carrier current; the 505-kc. current is the *upper side band* and the 495-kc. current is the *lower side band.*

Now suppose that the modulation wave is made up of a 1000-

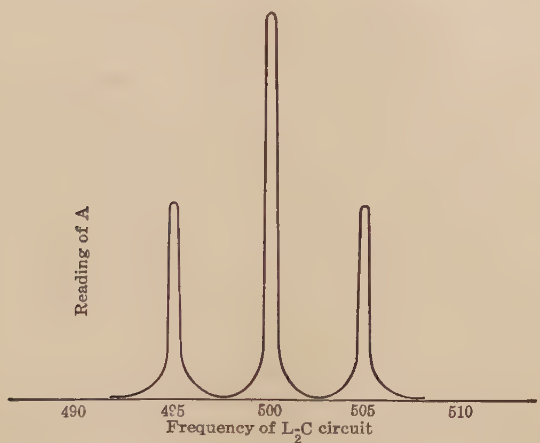

FIG. 123.—Response curve of the frequency meter of Fig. 122 if the current flowing through coil L_1 has the form of that shown in Fig. 121.

cycle wave with its third harmonic, 3000 cycles; a modulated wave of this form is shown in Fig. 124 (*a*), and in (*b*) of this figure is shown the frequency analysis of such a modulated wave. There are five frequencies making up such a wave, namely, 497, 499, 500, 501 and 503 kc. And now suppose that the carrier current is modulated by the sound waves of an orchestra, frequencies extending from about 50 per second to 5000 per second. The apparatus of Fig. 122 would yield a curve for this case as shown in Fig. 125. The upper side band would reach from 500,050 to 505,000 cycles per second and the lower side band from 499,950 to 495,000 cycles. Unless the tuning of the frequency meter is extraordinarily sharp

the form of the resonance curve has the appearance of that given in Fig. 126, the dips between the carrier frequency and the nearest side-band frequencies being obliterated by the resistance of the frequency meter.

As mentioned before, the sound waves of the voice cover frequencies from about 100 to 6000 for the male and 200 to 8000 for

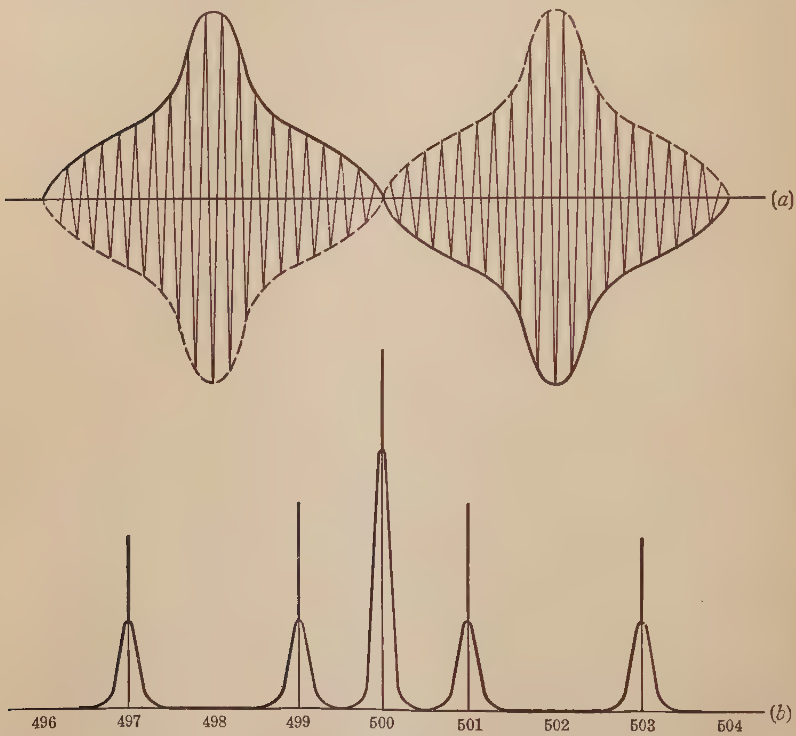

FIG. 124.—More complicated modulation and the frequency-meter response curve.

the female voice. Thus if a 300-meter station (1000-kc.) is voice modulated the antenna current will contain frequencies from 994 kc. to 1006 kc. for the male voice and from 992 kc. to 1008 kc. for the female voice. To receive all of the components of such waves properly the resonant circuits of the radio receiver must be tuned broadly enough to admit equally well all frequencies from 992 to 1008 kc. If the receiving circuit is tuned too sharply (low

resistance due to regeneration may do this) the highest radio frequencies and lowest radio frequencies are cut off. Thus in Fig. 127

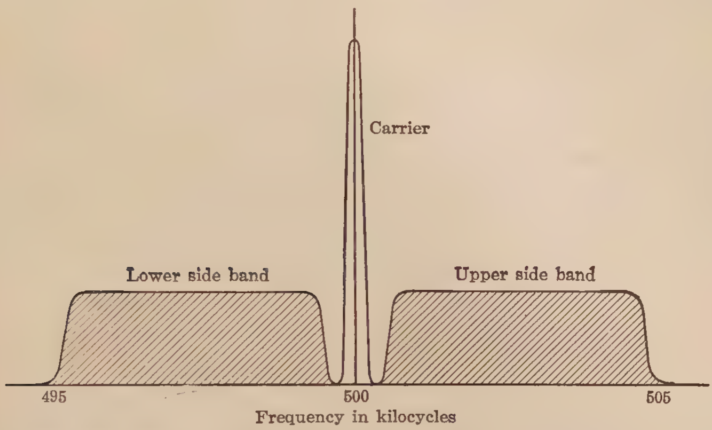

FIG. 125.—Frequency-response curve (theoretical) of a frequency meter excited by an orchestra-modulated wave.

at *B* is shown the frequency characteristic of the orchestra modulated wave of Fig. 126 and at *A* is shown the resonance curve of the

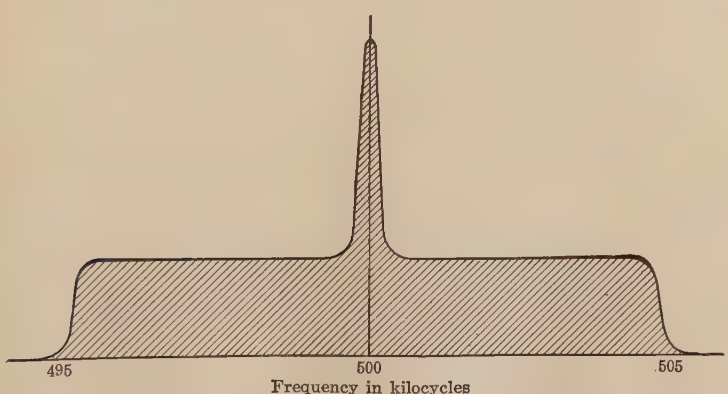

FIG. 126.—Probable response curve of an actual frequency meter for the conditions of Fig. 125.

receiving circuit and in the shaded area are indicated the frequencies of the side bands which are practically eliminated by the resonance quality of the receiver.

But the frequencies which are eliminated in the receiver circuits are those put into the modulation of the carrier current by the high notes of the orchestra. Hence when the modulated current is detected and supplied to the loud speaker the high notes of the orchestra will be missing.

If this happens when receiving a voice modulated wave the loud speaker " voice " will be lacking in consonants; it is the consonants which utilize the highest voice frequencies and these appear in the voice-modulated wave as the outer parts of the side bands. If these side bands are then cut off by the selectivity of

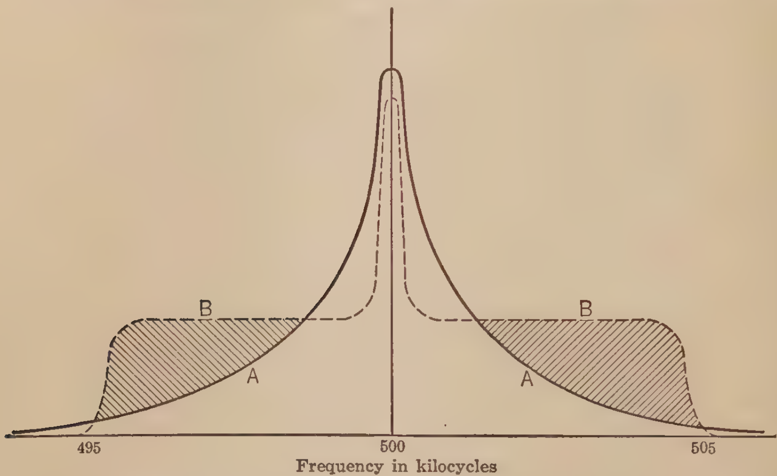

FIG. 127.—Showing how a receiver, adjusted for great selectivity, fails to respond to the upper frequencies of modulation.

the receiver, the consonants are lost and the reproduction of the voice will be indistinct and " drummy."

9. Typical Circuit Arranged for Modulation.—In Fig. 128 is shown a simple scheme for sending out voice-modulated radio frequency current. The type of oscillatory circuit used is different from those previously discussed, in that the oscillatory circuit, that is, the circuit which fixes the frequency, is connected with neither grid nor plate. The antenna capacity, in combination with the inductance A, fixes the frequency of the oscillatory current. The power is supplied to the oscillatory circuit, from the plate-circuit battery, through the coupling of coils C and A. The exciting voltage for the grid, to maintain the oscillations, is obtained

through the coupling between the grid coil B and the coil A in the oscillatory circuit. The condenser above the letter S in Fig. 128 is to by-pass the high frequency currents, set up in the grid circuit by coil B, around the secondary coil S of the iron core transformer P–S.

The circuit as so far described sets up in the antenna radio-frequency currents of fixed amplitude. The rest of the apparatus, namely transformer P–S, microphone and battery in series with P, are for *modulating* this radio-frequency current. When the microphone is spoken into, the current through it varies in accordance

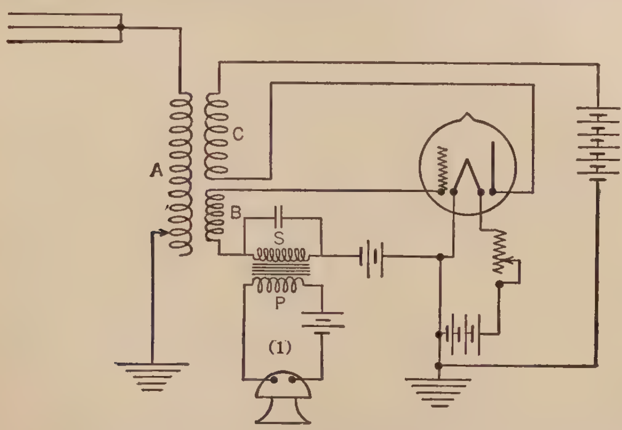

FIG. 128.—A simple transmitter circuit, arranged to send off a voice-modulated wave.

with the voice frequency and this varying current flows through the primary P of the transformer, which generally has a step-up ratio of perhaps 10. There is thus set up in S a voice-frequency voltage of a few volts. The condenser across the secondary has a very low reactance for the radio-frequency currents, but for the voice currents, of frequencies about 1/1,000 as great, the condenser is of such high reactance as to draw practically no current from the secondary. Thus the voltage on the terminals of the secondary coil is practically of the same form as that on the primary, and this is reasonably similar to the form of sound wave impinging on the microphone.

There are thus acting in the grid circuit of the triode of Fig. 128 three distinct voltages. The C battery holds the grid at some

suitable negative voltage on the average. The transformer secondary S, introduces a voltage into the grid circuit, which makes the grid potential vary, with voice frequency, about the value fixed by the C battery. And in addition while the grid voltage is thus varying with voice frequency, the coil B is impressing on the grid a radio-frequency voltage.

With no voice-frequency voltage acting, the radio-frequency current in the antenna is of constant amplitude, and this amplitude

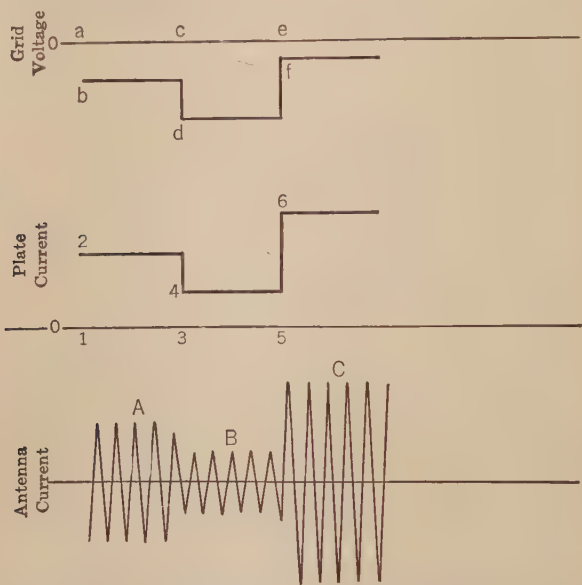

FIG. 129.—Voltage and current curves to explain the action of the circuit of Fig. 128.

is determined by the average value of plate current. About 25 per cent of the power delivered to the plate circuit by the B battery is changed into alternating-current power in the antenna so that as the plate-circuit current is increased or decreased (as might be done by changing the B battery) the radio-frequency current in the antenna will also increase or decrease.

But the average plate current can be controlled even if the B battery remain fixed, because the plate current is controlled by the grid voltage as well as by plate-circuit voltage. This is indicated in Fig. 129; during the time the grid potential is held at the nega-

tive value *ab* the plate current is equal to the value 1–2 and the antenna current has amplitude A. If now the grid bias is increased to the value *c–d*, the plate current drops to the value 3–4 and the amplitude of antenna current drops to B. If now the grid bias is decreased to less than its normal value, as at *e–f*, the plate current correspondingly increases to 5–6, and the antenna current increases to amplitude C.

Now returning to Fig. 128 it is evident that the transformer *P–S* does raise and lower the voltage of the grid around the average value fixed by its C battery, and that this raising and lowering is carried out at voice frequency, in accordance with the shape of the voice wave. Thus it follows that the amplitude of the radio-frequency current in the antenna circuit goes up and down in a manner fixed by the shape of the voice wave striking the microphone. And finally it follows that the radio wave sent out from the antenna goes out with intensity variation, the variation "carrying" the form of the voice wave. Because of this analog, the unmodulated antenna current is called the *carrier current* and this sends out the *carrier wave.*

The scheme outlined above is called *grid modulation* as it is brought about by the grid, going up and down in potential at voice frequency, controlling the plate current and hence controlling the antenna current.

10. Plate-circuit Modulation.—The scheme shown in Fig. 128 has been much used in small radio-phone transmitting sets, but the larger broadcasting stations, as installed today, nearly always use *plate-circuit modulation,* in which the plate voltage of the oscillator is forced to fluctuate in accordance with the voice wave. The commonly employed circuit for using plate-circuit modulation is shown in Fig. 130. In the large broadcasting stations many triodes are used, not two as shown in this figure. The output of the triode marked "oscillator" instead of being supplied to the antenna is fed to the first of a series of cascaded triodes of continually increased rating, the last tubes being of 10-kw. rating or more.

The scheme used in Fig. 130, it will be noticed, is apparently not as efficient from the standpoint of apparatus as the scheme of Fig. 128. There only one tube is used for carrying out both functions, of oscillator and modulator, whereas in the scheme of Fig. 130 one triode is used for modulator and a separate one for oscillator; in the better transmitting sets there are actually more modu-

lator tubes than there are oscillators. As to which scheme is really more efficient there is still argument.

The scheme of plate modulation depends primarily upon the action of the iron core inductance, or choke coil, *D*. It will be noticed that both triodes draw their plate currents through this coil, which is of very high reactance for voice frequencies. Its reactance is so high that in the operation of the circuit the current through it remains nearly constant; because of this the scheme has been called the "constant-current" scheme.

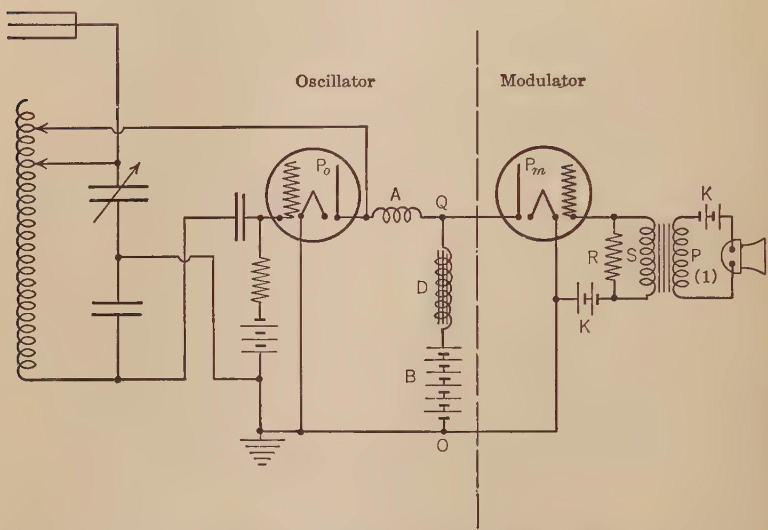

FIG. 130.—The plate-circuit modulation scheme used in practically all of the broadcast transmitters.

The microphone circuit operates on the grid of the modulator tube, making this go up and down in potential in accordance with the voice waves impinging on the microphone. As the grid of the modulator goes up and down in potential, so must the plate current of this tube. But because the total current through choke coil *D* must remain essentially constant (due to its high reactance), as the modulator-plate current goes up and down the oscillator-plate current must go correspondingly down and up. Thus the plate current of the oscillator follows in form the voice waves actuating the modulator, and, as the oscillating power fed to the antenna circuit depends directly upon the amount of current in the plate

circuit of the oscillator, it is evident that the oscillatory power in the antenna follows the form of the voice waves actuating the microphone.

The coil *A* is a radio-frequency choke coil, to prevent the oscillator from feeding part of its high-frequency energy into the plate circuit of the modulator; the resistance *R* is to make the microphone circuit more nearly uniform in response for all the voice frequencies than it would otherwise be.

In Fig. 131 there is shown a series of curves in order to follow out more closely the various actions involved in the plate-circuit modulation scheme.

In Fig. 132 there is shown in some detail the circuit arrangement of a modern 5-kw. broadcast transmitter. The terminals marked "speech input" are connected to the output terminals of a "speech amplifier" consisting of a series of cascaded tubes so arranged that the few microwatts of the voice waves control an output of about 5 watts. This power, through a potentiometer arrangement, is supplied to the "speech input" posts.

The 250-watt triodes have their plate voltage supplied by the 1500-volt generator and their filaments are supplied by the 14-volt generator. In both these circuits filters are used to eliminate the

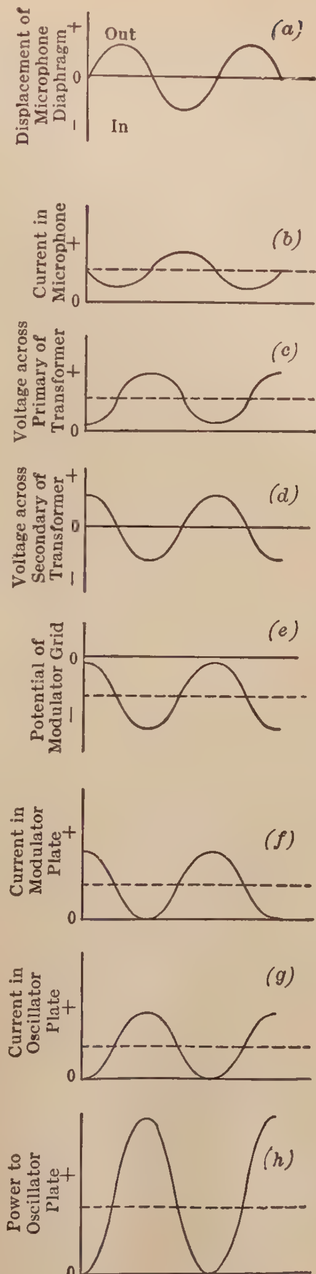

FIG. 131.—Curves to explain the action of the circuit of Fig. 130.

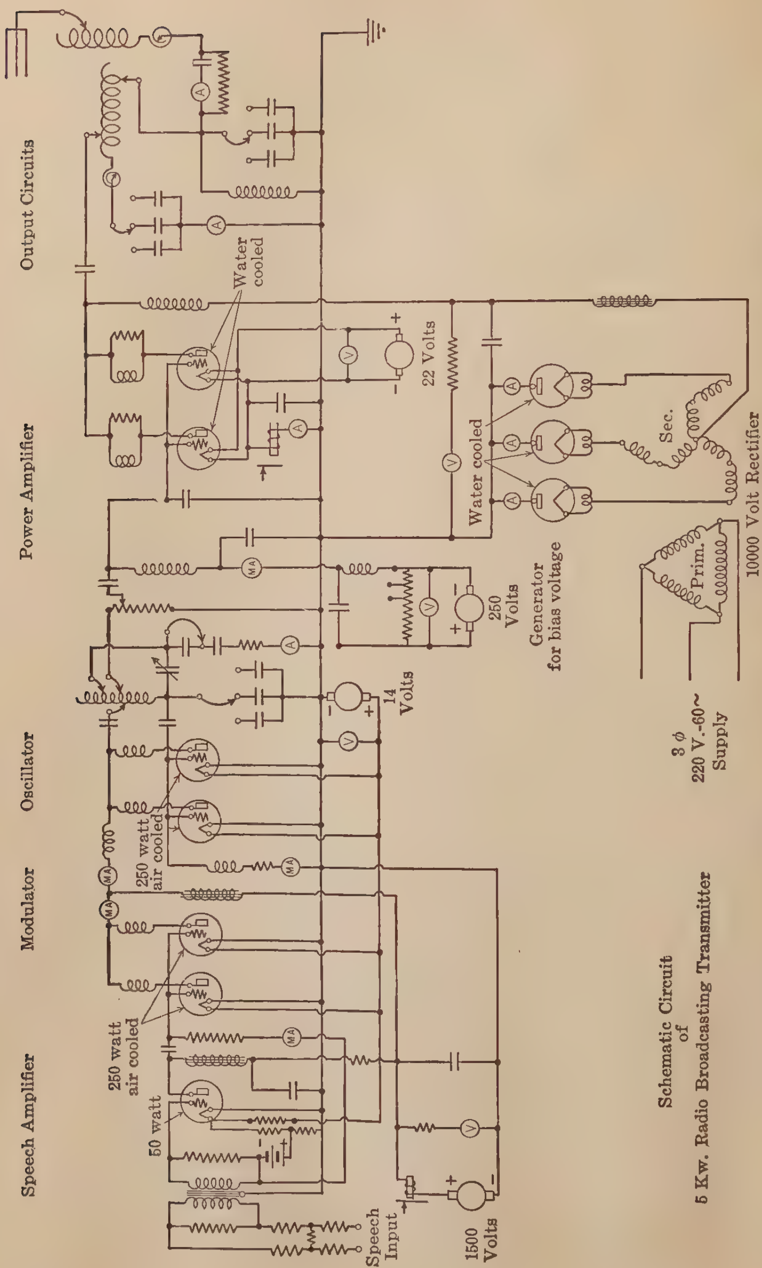

FIG. 132.—Circuit diagram of a modern 5-kw. transmitter for a broadcast station.

commutator hum; the filament-circuit filter has coils weighing hundreds of pounds and condensers measured in thousands of microfarads. A 250-volt generator, with potentiometer circuit, furnishes the proper bias for the various tubes. The tubes which furnish power to the antenna are of the water-cooled type; their plate voltage is obtained from a 3-phase alternating-current power supply, through three diodes and suitable filters. Many details such as filters, wave traps to eliminate harmonics, protective devices to shut off plate-circuit power if the triodes or diodes overheat, etc., are necessarily omitted in the simplified diagram of Fig. 132.

11. Action of Detector in Radio-phone Reception.—The current set up in the antenna of the radio-phone receiving circuit is, of course, of radio frequency; it is modulated at voice frequency but as the current itself is outside the audible range the variations in amplitude, even though of voice frequency, can not be heard. A rectifying device must be used which changes the *voice-modulated radio-frequency current* into a *voice-frequency current.* The triode detector serves this purpose better than any other device.

As was shown in section 21 of Chapter IV, the triode detector, when used with grid condenser and grid leak, supplies a plate current the average value of which goes down as the amplitude of the radio-frequency signal on the grid increases. This is illustrated in Fig. 133. The circuit arrangement shows a condenser C, shunting the phones; this is to permit the high-frequency fluctuations in plate current to take place without the choking effect of the phones. The high-frequency component of the plate current, then, flows through condenser C, and as the average value of plate current changes the current through the phones changes.

For a radio signal of the form shown in (b), Fig. 133, the plate current has the form shown in (c). The average value of the plate current is indicated in dotted lines, and this is the current that flows in the phones. It is thus seen that the variations in the phone current follow in form the variations in amplitude of the radio-frequency signal. If, then, the radio-frequency signal has an amplitude variation corresponding to the voice, the phone current corresponds in form to the voice.

One precaution which must be observed in arranging the detector circuit has to do with the *time constant* of the grid condenser and leak. The average potential of the grid must be capa-

ble of changing in accordance with the amplitude of the voice-modulated wave, and if the time constant, RC, of the grid condenser and leak, is too high, rapid changes in amplitude cannot be followed. To reproduce the consonant sounds of the voice properly, the product, RC (R in ohms and C in farads) should not exceed 0.0001 second. If too large a time constant is used the consonant sounds of the voice will not be given off by the phones, although the

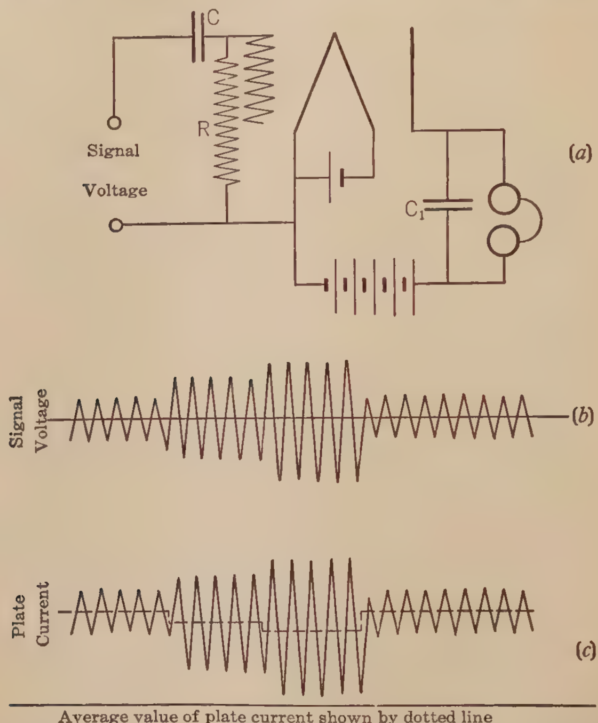

FIG. 133.—Showing how the detector functions to give a plate current with an average value following the modulation of the signal voltage.

vowel sounds are reproduced perfectly well; these vowel sounds are given by comparatively slow changes in the amplitude of the radio-frequency current, and the grid potential will follow these when it cannot follow the rapid changes which represent the consonants.

12. Effect of Selectivity of Set on Quality of Speech.—A radiophone receiving set must be selective enough to be able to " tune

in" one signal to the exclusion of others of nearly the same wave length, or frequency. Thus if the desired signal is of 800-kc. frequency and there are two other stations sending at the same time, say of 780-kc. and 820-kc., these two undesired signals should be inaudible when the set is tuned for the 800-kc. signal.

This characteristic of the set, its discriminating ability, so to speak, is called its *selectivity*. The tuned circuits used in the radio-

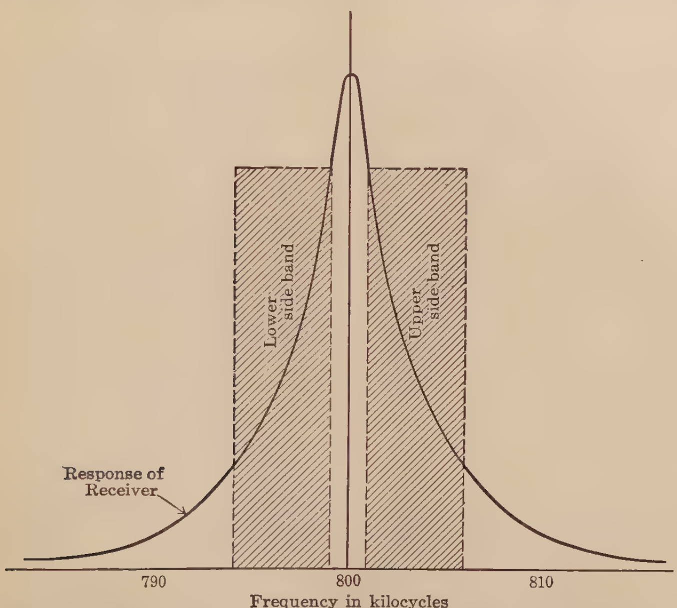

FIG. 134.—A receiver with too much selectivity cuts out all of the upper frequencies of voice or music.

frequency amplifier of any modern receiver do give this desired selectivity, if good coils and condensers are used. If three tuned radio-frequency circuits are used (the ordinary arrangement) the selectivity is many times as good as if only one tuned circuit is used. A possible selectivity curve for such a receiving set is given in Fig. 134. All three circuits are tuned for 800 kc., resulting in the sharp resonance curve shown. If we assume that the audible frequency band extends from 50 to 8000 vibrations a second the two side bands of the 800-kc. signal would extend from 792 kc. to 799.05 kc. and from 800.05 kc. to 808 kc. For fidelity of repro-

duction the radio receiving set should respond equally well to all of these frequencies. But the selectivity curve of Fig. 134 shows that the response for the 792-kc. and 808-kc. currents is only about one-fourth as great as for those frequencies close to the carrier frequency.

Now the outer regions of the side bands, that is, those frequencies farther from the carrier current, carry the consonant sounds of the voice while those near the carrier frequency carry the vowel sounds. Hence it appears that a set with too great a selectivity gives a greater response to the lower voice frequencies than to the higher, resulting in poor intelligibility. It was pointed out in section 3 of this chapter that the distinctness, or intelligibility of speech, depends mainly upon the frequencies above 1000. Some very selective sets have a selectivity so sharp as to actually make speech sound "drummy," resulting from too great an amplification of vowels compared to that of consonants. The modern radio receiver reproduces in about their proper proportions frequencies as high as 5000; for frequencies higher than this the response of the receiver falls off.

13. Trans-Atlantic Telephony.—At the time of this writing radio telephony is being used regularly for conversations between any part of the United States and almost any part of Europe.

Suitable land lines convey the speech currents to the radio-transmitting stations, where it is amplified and used to modulate the power of reasonably large triodes. The modulated radio-frequency current thus obtained is put through filters, and the *carrier and one side band are suppressed.* The one side band remaining is used to excite larger triodes, in cascade, until from the last series of large water-cooled tubes about *200 kw. of single side-band modulated power* is obtained and sent out to the antenna.

At the receiving station on the other side of the ocean, this single side band is picked up and there it is combined with a locally generated carrier current of exactly the same frequency as the carrier which was suppressed. Not only is the frequency of this locally supplied carrier the same as the original but its amplitude is adjusted to *that value the suppressed carrier would have had, if it had traversed the ocean with the single side band.* The single side band and this locally supplied carrier are suitably amplified, detected, and sent over land lines to the listening party.

On each side of the Atlantic the receiving station is located

many miles from the transmitter, and its antenna is of the directively selective type. Many refinements are employed to prevent interference between the " going " and " coming " signals, which both use the same frequency. Due to the selectivity of antennas, elimination of carrier and one side band, choice of location for receiver where " static " is low, etc., it is estimated that the 200 kw. of power actually employed is as effective, across the ocean, as if 6,000,000 kw. were used as in ordinary broadcasting, with none of these special features incorporated. That is, if an ordinary broadcast receiver, with the usual antenna, etc., were required to give as reliable communication over the same distance, from a broadcasting station sending both side bands and carrier as is ordinarily done, the station would have to generate 6,000,000 kw. of power.

In Fig. 135 there is shown a schematic layout of the present radio telephone channel from New York to England. The normal channel uses a 60-kc. frequency, but as there are times when high frequencies cross the ocean with less attenuation than the 60-kc. channels, another channel of 1,360 kc. is used in addition. In England the receiving operator tunes in on the channel giving the better transmission. Since the picture of this radio channel was made the receiving station in England has been moved into Scotland at Cupar. It was found that the average signal-to-noise ratio at Cupar was six times as good as it was at Wroughton. This relocation of the receiving station has increased the reliability of the channel as much as would have been done by changing the power at the transmitter from 200 kw. to 1000 kw.!

14. The Broadcasting Station.—A broadcasting station consists essentially of

(*a*) The studio, microphone and speech amplifier.
(*b*) The radio-frequency system, including oscillators and modulators.
(*c*) The power equipment.
(*d*) The control equipment.

(*a*) The studio must be very carefully arranged to prevent undesired echoes; therefore the walls, floors and ceiling must be of such material as will give but little reflection of sound. Carpets and rugs on the floor and heavy hangings around the walls will effectually deaden the echoes. The ceiling is generally made of

some semi-porous material which absorbs sound. Too much deadening effect is to be avoided, however, as it is difficult to sing

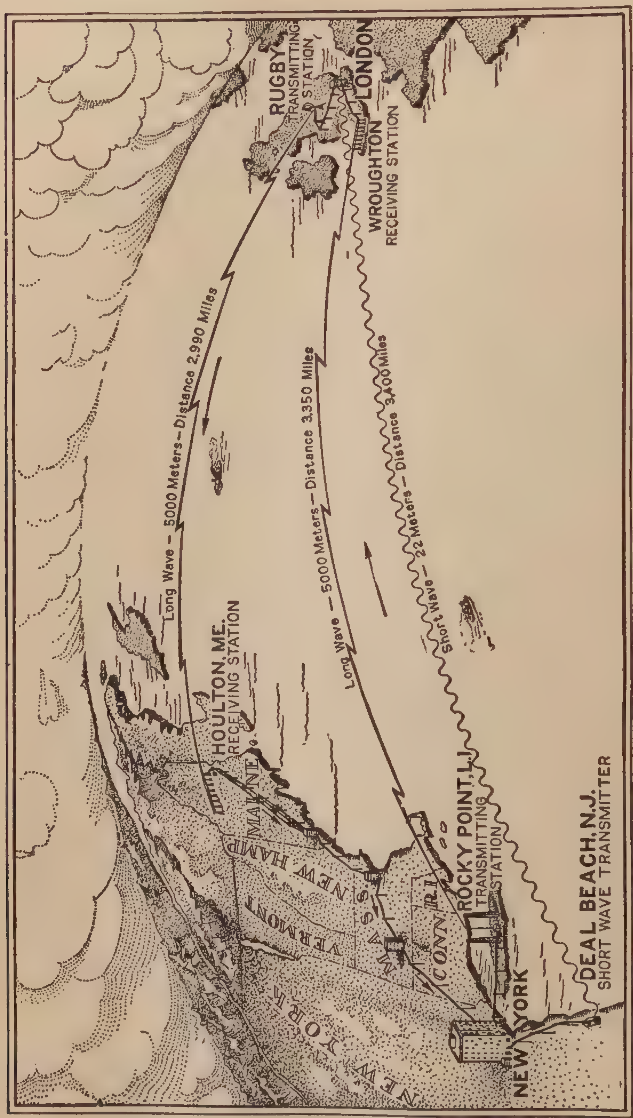

Fig. 135.—A bird's-eye view of the trans-Atlantic radio-telephone channel. Since this diagram was made the receiving station at Wroughton has been moved to Cupar, in Scotland, with a gain in ratio of signal to static of five times.

or talk naturally in a "dead" room, so a compromise must be reached. A typical studio is shown in Fig. 136. The microphone

is generally of the double-button type, held in a spring suspension at about the right height to be spoken into. In Fig.

FIG. 136.—The broadcast studio must be carefully arranged to prevent troublesome echoes, etc. Curtains, rugs and ceiling lining are properly chosen to cut down reverberations to that amount which makes the received signal sound natural.

136 two microphones, so supported, can be seen, close by the piano.

The current from the microphone is supplied to the input ter-

minals of a "speech amplifier"; this is really a high-quality audio-frequency amplifier, with suitable controls for adjusting its amplification. A typical arrangement of apparatus is shown in Fig. 137; the two potentiometer controls, V_1 and V_2, serve to control the amplification to any desired amount.

The power range of an orchestral selection may frequently be 100,000 to 1, but it is practically impossible to design a broadcasting station to care for such great variations, at a reasonable expense. It has been found that a power range of 1000 to 1 results in reproduction by a good radio receiver sufficiently like the

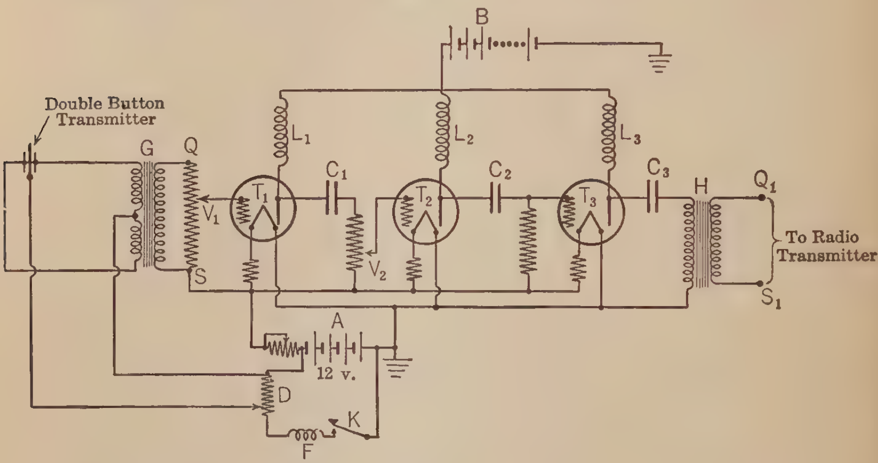

FIG. 137.—A circuit diagram of a speech amplifier; two potentiometers, V_1 and V_2, enable the operator to maintain the amplification at the desired level.

actual rendition to be satisfactory; the range of output by the speech amplifier is held to about this amount by the control operator who watches one of the milliammeters and so adjusts the controls, V_1 and V_2, as to increase the volume of the pianissimo passages and to tone down the heavier passages.

(*b*) The radio-frequency system consists of a series of oscillators, modulators, and power amplifiers. In addition there must be a standard piezo-electric oscillator used either actually to control the frequency of the station or to serve as a reference frequency to which the frequency of the station is closely held, by listening to the beat frequency and keeping this within the limits set by government order.

(*c*) The power equipment for the smaller stations consists of a motor, driving two continuous current generators; one of these develops 1500 to 2000 volts for the plate supply and the other 15–20 volts for the filaments. The generator voltages are controlled by suitable field rheostats, and filters are used to eliminate the commutation ripple.

For stations of more than 1-kw. rating water-cooled triodes are used and the plate supply of from 10,000 to 20,000 volts is generally obtained from a bank of rectifiers. The three-phase power supply of the station is frequently changed to six-phase, and six water-cooled diodes rectify this to give a voltage almost free from ripple; what ripple there is must be flattened out by suitable chokes and condensers.

Small generators are generally used for getting the required grid bias for the various triodes.

The general arrangement of the apparatus was shown in Fig. 132.

(*d*) The control equipment includes, in addition to the field rheostats and volume control already mentioned, a "mixing panel" from which the operator is able to pick up his signal from any one of several microphones placed in the studio or music hall. He may sometimes "fade out" one of them as he gradually brings in the other.

The water-cooled tubes require pumps, etc., and suitable safety relays, operated from the temperature of the cooling water. Proper retard circuits enable the various operations, lighting filaments, starting water supply, putting on grid bias, putting on plate voltage, etc., to take place in proper sequence and at the proper time intervals.

Ammeters are provided for antenna current, also for plate and grid circuits of both oscillator and modulator. The ammeter in the plate circuit of the modulator responds to changes in speech volume and thus serves as a correct measure of the degree of modulation. Too small a modulation results in weak signals at the listening stations and too high a modulation results in poor quality of signal and broad tuning at the receiving set.

Some of the modern stations are arranged to broadcast the same program at two or more wave lengths, using two different transmitters and antennas but the same speech amplifier. The longer wave is for listeners within a hundred miles or so and the short wave is for listeners who are thousands of miles away.

The complete cost of a modern 5-kw. broadcast station may be as much as $150,000. The studio is generally in some large city and the transmitter itself 25 miles or so out in the country. High-grade loaded telephone cables connect the output of the speech amplifier, at the studio, to the modulator tubes at the station. The antenna is generally suspended from two self-supporting steel towers, about 150 feet high. Spare equipment of all kinds must be kept in instant readiness for replacing parts which fail; the station must not be " off the air " for repairs frequently as it will otherwise lose its only asset, the radio listeners.

When the time of a station is sold, for advertising purposes, the charge for the station alone may be from $500 to $5000 an hour, depending upon its reputation and power, that is, its number of listeners. In addition to this charge, of course, the advertiser must pay for the talent used in the program.

CHAPTER VII

RECEIVING SETS

1. Simple Crystal Receiving Sets.—For the listener within a few miles of a broadcasting station, who is satisfied with the telephone head set for receiving the signal, a crystal detector set is perfectly satisfactory. The quality of a signal received in this fashion is much better than that given by the average multi-tube set with loud speaker. The arrangement of apparatus is shown in Fig. 138.

The antenna should be a single wire as high as convenient and about 150 feet long. The combination of L_1 and L_2 is called a loose coupler; L_1 consists of a few turns of heavy wire and L_2 has ordinarily several times as many turns of fine wire. The coil L_1 is continuously variable (by sliding contact or switches) so that the antenna may be tuned to the signal frequency. Coil L_2 is fixed in amount of inductance, but is adjustable in position with respect to L_1, so that the coupling can be varied. The condenser C_2 is of the rotating plate type, of maximum capacity about $0.0005 \mu f$. A suitable inductance for L_2, for such a condenser, is $200 \mu h$.

The crystal rectifier D is of galena, silicon, or is possibly the double crystal rectifier, zincite in contact with chalcopyrite. The head phone P should be of the high-resistance type, having a continuous current resistance of about 1000 ohms and one henry inductance. Such a phone will give an audible signal when the current through it is about one microampere.

In picking up a signal, tight coupling is used between L_1 and L_2, L_1 and C_2 being adjusted simultaneously until the desired signal is obtained. Then to cut out interfering signals the coupling is diminished, keeping L_1 and C_2 constantly in adjustment for the desired signal, by trial. A coupling of not over a few per cent will generally give the best results. The power required for a comfortable signal in the head phone is about 0.025 microwatt. If the phones receive $\frac{1}{2}$ per cent of the power received by the antenna, this will amount to 5 microwatts. If the effective resistance of the

antenna is 25 ohms the current required in the antenna is about 450 microamperes. This requires that the voltage induced in the antenna by the signal wave is about 0.01 volt. If the antenna is 30 feet high this requires that the strength of the signal wave be one millivolt per meter.

The crystal detector set, it will be noticed, depends for its operation upon the energy picked up by the antenna; *the power available for the phones is only a small fraction of that picked up.* This differs entirely from the action of a triode receiver, which uses the signal picked up by the antenna *to control a local supply of*

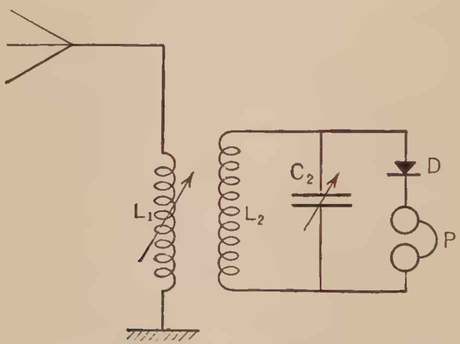

FIG. 138.—Simplest serviceable receiving set; its sensitivity and selectivity are poor but the quality of signal is good.

energy, thousands of times as great as that picked up by the antenna.

The crystal set has largely disappeared in America but is the prevailing type of receiver in Europe; its low first cost, freedom from battery troubles and expense, and good quality of received signal, make it in many cases preferable to a vacuum-tube set.

2. Simple Triode Receiver.—In this scheme the crystal detector is replaced by a three-electrode vacuum tube, arranged as a detector; the connection scheme is given in Fig. 139. This has the advantage that the triode is a more sensitive and reliable detector than is the crystal, and that the tuning of the L_2–C_2 circuit is sharper than when a crystal detector is used. The grid condenser, C, is generally $0.0002\mu f$ and the grid leak about 1 megohm. The plate battery is about 25 volts. The triode itself is several times as costly as the crystal detector, and the filament

battery and plate circuit battery constitute extra expense and trouble of maintenance.

A signal power of 0.025 microwatt in the phones in this circuit requires a power in the antenna of about 0.5 microwatt, or about one-tenth that required for the same signal strength when a crystal detector is used.

3. Regenerative Triode Receiver.—The simple triode detector arrangement of Fig. 139 is only about ten times as sensitive as a crystal set, as the above calculations show. But, as the plate circuit battery has plenty of energy, and as by coupling the plate cir-

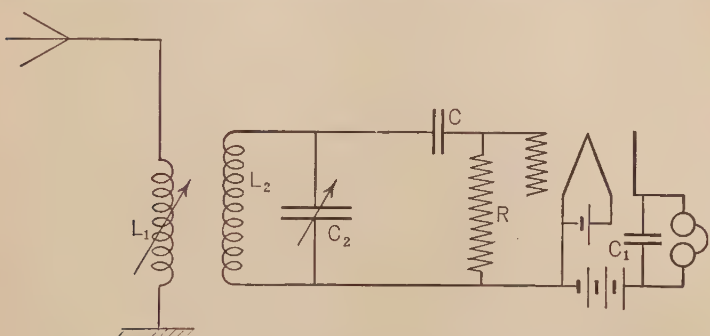

FIG. 139.—Non-regenerative triode receiver; same characteristics as circuit of Fig. 138, although about ten times as sensitive.

cuit to the grid circuit it is possible to have the plate current fluctuations reinforce the signal current in the grid circuit, by the simple expedient of a "feed-back" arrangement the triode detector becomes hundreds of times as effective as the crystal. The circuit arrangement is shown in Fig. 140; this is seen to be identical with that of Fig. 139 with the exception of the small coil L_3, interposed in series with the plate circuit and magnetically coupled to the coil L_2, in the tuned grid circuit. The coupling between L_3 and L_2 must be of the right polarity, and variable in amount. The coil L_3, called the *tickler coil*, is generally of much smaller inductance than L_2, perhaps one-tenth as much.

The effect of this feed-back, or regenerative, coupling is essentially to lower the effective resistance of the L_2–C_2 circuit. If this resistance is measured, in an alternating-current Wheatstone bridge it will be found to diminish as the tickler coupling is increased; with coupling greater than a certain amount the measured value

of the resistance of the L_2–C_2 circuit is actually negative. If nothing were done to prevent it, the circuit would oscillate under this condition of coupling.

Now the impedance of the L_2–C_2 circuit is made up of reactance, and resistance. By properly adjusting the variable condenser C_2, to keep the circuit tuned, the reactance of the circuit, for the signal current, is kept continually equal to zero. By increasing the tickler coupling the resistance of the L_2–C_2 circuit is diminished and hence, for the signal frequency, the circuit impedance may be made to approach zero. In Fig. 141 are shown the impedance curves of

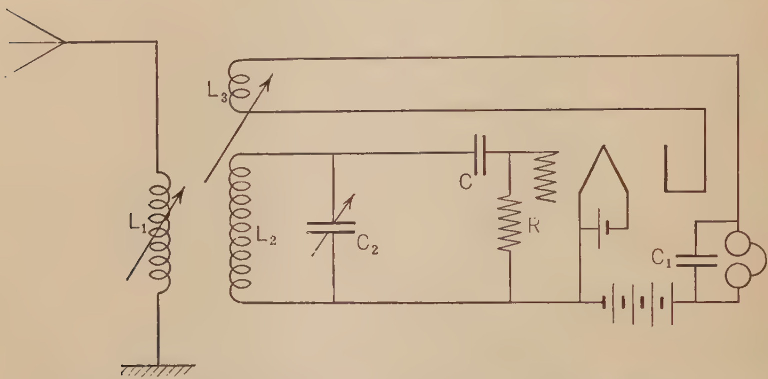

Fig. 140.—Regenerative triode receiver; in the hands of a skilled user it is sensitive and reasonably selective but when adjusted for high sensitivity its quality is poor.

circuit L_2–C_2 for various frequencies, and for three values of tickler coupling, curve 1 being for weakest coupling and curve 3 for the tightest coupling.

It will be realized at once that for the tuned frequency, and for the coupling used in curve 3, very large signal currents will flow, even if but small voltages are induced in the L_2–C_2 circuit from the antenna.

The performance of the circuit, in so far as signal strength is concerned, as the regenerative coupling is increased, is shown in Fig. 142. The signal strength increases tremendously in volume, until at a certain critical coupling the circuit "breaks" and self-sustained oscillations are set up in the L_2–C_2 circuit.

Above this critical coupling the signal is still heard, with great

volume as indicated by the dashed part of the curve, but its quality is changed. In case a spark signal is being received, its normal

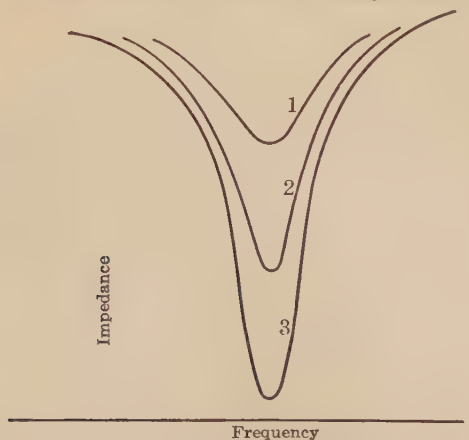

FIG. 141.—Selectivity curves of the regenerative receiver for different degrees of feed-back.

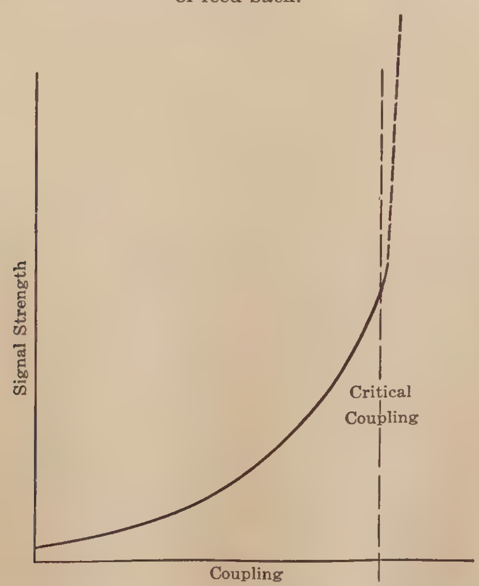

FIG. 142.—Behavior of a regenerative receiver when used for spark telegraphy reception.

musical note changes to a rasping, scratchy one, and in case a radio telephone signal is being received, a loud whistling note will gener-

ally be heard, as the critical coupling is exceeded. The whistle is the beat frequency between the local oscillations and the carrier current of the telephone channel. Of course if the carrier current and the local oscillations have exactly the same frequency no beat note will be heard, but this does not generally occur.

A carefully adjusted regenerative triode circuit can be made so sensitive that trans-Atlantic continuous-wave telegraph signals can be easily read, with the simple circuit of Fig. 140. Such extreme sensitivity is obtained, however, only by a skilled operator; it requires very accurate adjustment of both tuning and regeneration.

4. Disadvantage of Regenerative Set.—The regenerative set shown in Fig. 140 has proven to be one of the greatest nuisances there is today in the field of radio broadcasting; several times attempts have been started to make such sets illegal.

When such a set is adjusted for the oscillatory condition, oscillatory currents flow not only in the L_2–C_2 circuit but also in the antenna, which is coupled to this circuit. The set then acts like a miniature transmitter, radiating waves of the frequency fixed by the L_2–C_2 circuit. This radiated power, small as it is, interferes greatly with reception by all other receiving sets in the vicinity. Beat frequencies are set up with stations to which neighbors are listening, resulting in whistles so loud as to drown out normal reception.

Thus suppose that the L_2–C_2 circuit is set for 860 kc. and that a neighbor has his set tuned for a 865-kc. station, to whose program he is listening. The 860-kc. wave from the oscillating receiver will beat with the 865-kc. carrier wave and produce in the listening set a piercing note of 5000 vibrations.

As the owner of the regenerative receiver changes the setting of C_2 (Fig. 140) the frequency of the oscillations sent out from his antenna correspondingly vary, and all of the neighbors are treated in turn to loud whistling notes of interference; these notes start at the top of the audible scale, descend to zero frequency and again increase, disappearing at the upper limit of audibility. Whereas the amount of power sent out by an oscillating receiver is very small, producing real disturbance only in the immediate neighborhood, it may be heard at a distance of a mile or more.

As long as the regenerative set does not oscillate, it does no harm to other listeners; anyone using such a set should always

keep the tickler coupling set at a value sufficiently low so that oscillations are not produced. This requires that as the capacity of C_2 is decreased, tuning the set for the higher frequency stations, the tickler coupling must be correspondingly diminished.

5. Requirements of a Modern Receiver.—The modern radio receiver must be sufficiently sensitive to " pick up " a station several hundred miles distant, with an antenna perhaps 50 feet high and 100 feet long. While it is receiving this distant signal it must not be interfered with by a powerful station close by, transmitting on a neighboring channel. That is, the set must be selective as well as sensitive. But it must not be too selective, otherwise the high notes in music and the consonants of speech will be improperly weakened.

The set must detect the signal, that is, reduce it from a modulated radio-frequency signal, to an audio-frequency signal. It must then amplify the audio-frequency signal without discrimination against any of the audible frequencies. It must deliver enough undistorted signal power to operate a loud speaker, that is, about 100 milliwatts on the average. For reasonably powerful low notes such as the pedal notes of an organ, it must be able to deliver ten times this amount of power if organ selections are to be reproduced with fidelity.

The above requirements practically determine what the receiver is to be. To gain sensitivity the radio-frequency signal must be amplified a good deal before detection; the efficiency of the detector tube, in changing the radio frequency to audio frequency, is proportional to the strength of the radio-frequency signal (see Fig. 105, p. 166). For weak radio signals the audio-frequency signal coming from the detector is so weak as to be hidden in the " noise," that is, static, tube noise, etc.

At least two stages of radio-frequency amplification are advisable; this means that the signal received from the antenna is increased 50 to 200 times in voltage before being sent to the detector.

By using a tuned circuit for the input circuit of the first radio-frequency (R.F.) triode, and tuned output circuit for both R.F. triodes, the signal goes through three tuned circuits in cascade. With well-constructed coils and condensers this will give as much selectivity as is advisable. Thus the two (and occasionally three)

R.F. stages of the modern receiver give both sensitivity and selectivity.

From the detector output circuit the signal (now of audio frequency (A.F.)) goes through an iron core step-up transformer to the first A.F. tube. The step-up ratio is about 3 to 1 and this, combined with the normal amplification of the triode, give audio-frequency voltage amplification about 25 per stage. The second A.F. triode is coupled to the first by another iron-core transformer, the output of this second A.F. tube is generally supplied directly to the loud speaker. The better sets use a special triode for the second A.F. stage (the output tube) as the type of tube used for the amplification stages does not have sufficient power output to operate a loud speaker properly. For good quality of signal the output to the loud speaker should not be more than about 5 per cent of the power supplied to the plate circuit by its B battery. A plate circuit supply of 90 volts and plate current of 0.003 ampere, which is about the rating of the average amplifier tube, will thus make available only a few milliwatts of high-quality signal.

The present tendency is to use more radio-frequency amplification and less audio-frequency amplification. A radio-frequency voltage amplification of 5000–10,000 is now feasible, and used in some sets. The signal delivered to the detector input terminals is as much as 20 volts (effective), making it possible to repeat directly from the detector tube to the power output tube.

By employing a special output tube, using say 300 volts for its plate supply, and drawing 0.05 ampere in its plate circuit, an undistorted output of 1,000 milliwatts is available. Such an output tube of course cannot be economically run from battery power, it requires rectified and filtered power from an alternating-current power circuit.

6. Loud Speakers.—Practically all of the better grade of radio receivers employ loud speakers, instead of head phones, for signal reception. Three types of loud speakers have been used in the past but it seems that only two, or possibly only one, will survive.

The early type of speaker had a vibrating diaphragm, the construction being much the same as that of a head phone, but of course of larger dimensions. Such a vibrating diaphragm is a very inefficient sound producer, and for low notes its efficiency is practically zero. To increase the efficiency long horns are fitted to take the sound waves from the diaphragm. Horns, unless scientifically

designed and built, give a peculiar barrel-like quality to speech. They should be made out of some "dead" material, should be built with the correct spread, or flare, must be sufficiently long to give the bass notes, and even then a horn type speaker is none too good. Attempts have been made to build a horn type speaker which will respond equally well over the audible range by using three elements, each with its own horn; one horn is about 1 foot long, another 3 feet long and the other about 10 feet long. Such a combination gives reasonably uniform response but evidently is expensive and cumbersome.

The cone speaker is built about as shown in Fig. 143. A paper cone *A–A*, with diameter about 18 inches and an apex angle of about 160°, is glued at its rim to another paper cone *B–B*. This one is frustrated and fastened to the metal

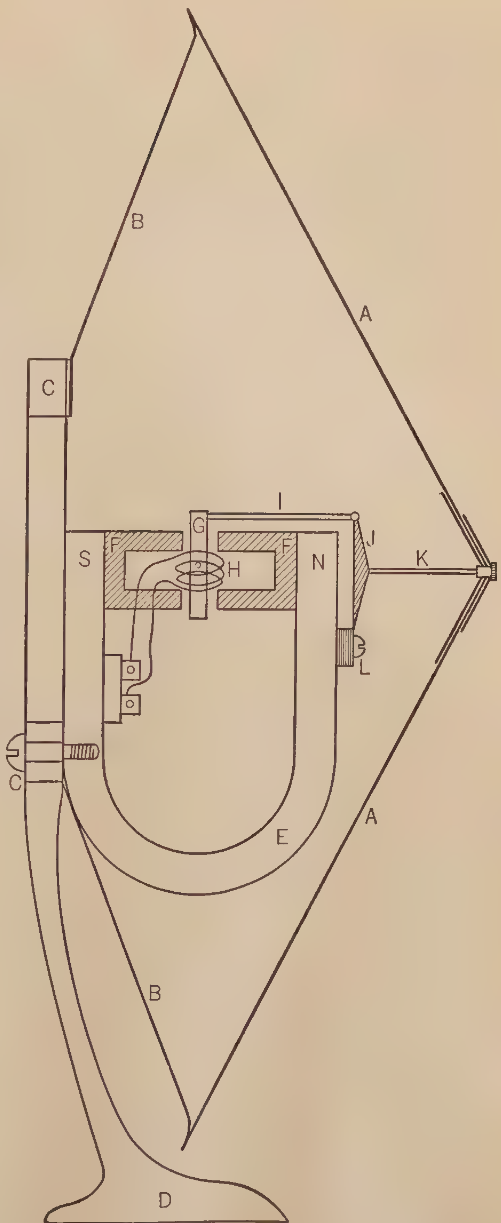

FIG. 143.—Construction of the ordinary cone loud speaker.

supporting ring *C*, which in turn is carried on the supporting base *D*.

Fastened to the ring *C* is a powerful motor of the balanced armature type. A heavy permanent magnet *E* is fitted with the laminated, slotted pole pieces *F-F*. A short steel reed *G* is held midway between these pole pieces by a flat stiff spring (not shown in the diagram) in such a way that it may rock about its center point. Surrounding this vibratory armature, and embedded in the pole slots, is a winding *H* of thousands of turns of fine wire. If current flows through this winding in such direction as to make the top (in the diagram) of the armature of north polarity the armature twists counter clockwise, against the retaining force of the flat supporting spring. If the current reverses, making the top of the armature *S*, the armature twists clockwise.

Fastened to the outer end of the armature is the stiff rod *I*, which fastens to the outer end of the lever *J*. This is of rigid construction except near its clamping support *L*, where it is flexible. Fastened to the center of lever *L* is the light stiff rod *K* which fastens to the apex of the cone by a small chuck.

This lever arrangement permits the outer end of the armature to move about twice as far as does the apex of the cone. With motors and cones of the ordinary dimensions the reduction of motion makes the cone diaphragm a more suitable mechanical load for the vibrating armature.

This type of loud speaker gives a much more truthful reproduction of speech and music than does the horn type. Like the horn type, it has a lower frequency limit, below which its efficiency as a sound producer falls almost to zero; this is in the region of 100 vibrations per second.

In its working range, say from 100 to 4000 vibrations, a good cone speaker has an efficiency of possibly 2–5 per cent. Its armature can vibrate but a short distance before striking the pole pieces so that the possible power input is limited to about one watt.

The most recent type of speaker goes by the name of *moving coil*, or *dynamic speaker;* its construction is roughly shown in Fig. 144. A shell-shaped magnet, having a central cylindrical core *F*, is excited by the winding *G*. The air gap of the magnet is ring-shaped, the end piece *H* of the shell reaching almost to the core *F*. The density of flux in the air gap is about 14,000 lines per sq. cm., and the power used in the magnetizing winding is from 3 to 15

watts. In the narrow ring-shaped air gap (in the average speaker about 0.05 inch long) is placed a light coil E, consisting of a hundred or more turns of fine wire. The frame on which the coil is wound is flared at its outer edge, for cementing to the paper cone D, having an apex angle of about 140°, and a diameter at its base of about 10 inches. At its outer edge the cone is cemented to a thin ring of flexible leather, such as kid, and this in turn is fastened to a light metal ring B. This ring B, faced with felt, is pushed tight against the baffle board A, which has a circular opening of the size of the cone D.

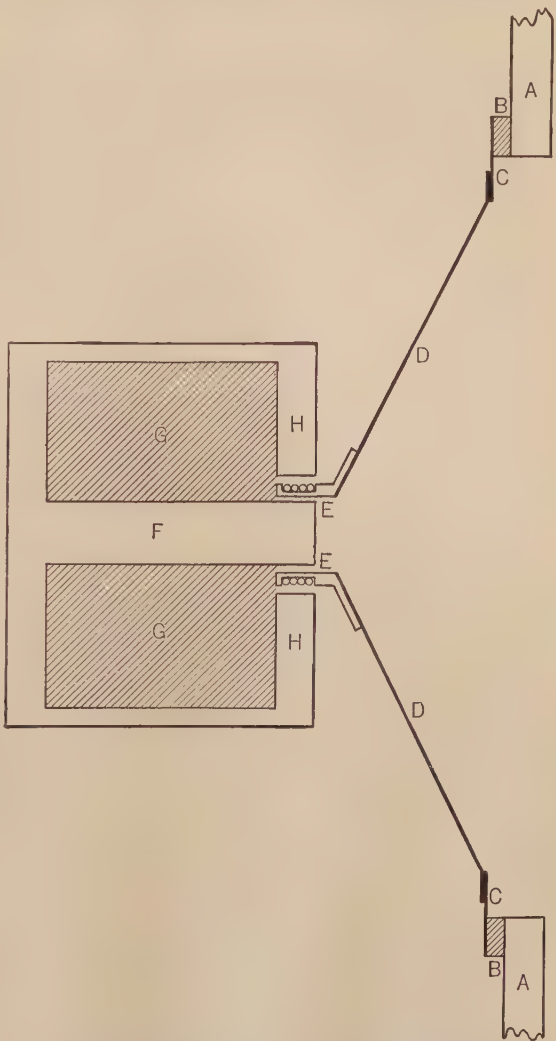

FIG. 144.—The moving coil, or so-called dynamic, speaker.

The voice currents flowing through coil E make this move axially, thus pushing the cone D to and fro. The baffle board acts to prevent the air from running around the edge of the cone as it moves, and helps greatly in forming the low-frequency sound waves.

This type of speaker supplied with a watt or more of electrical power will reproduce throughout the audible range better than any other type. From about 100 vibrations a second up, it is equal to the cone speaker, but below 100 it is very much better. It will reproduce well sounds as low as the ear can perceive, about 40 per second. In many of these speakers the response for the very high voice frequencies is comparatively too great, so a condenser-resistance filter is frequently used in shunt with the speaker to reduce this high-frequency response. This dynamic speaker is the only type which reproduces with fidelity the lower range of notes of an organ selection.

The winding G generally has many turns of fine wire, and its current is the rectified alternating current which is to supply the plate circuits of the triodes of the receiving set. It has a high inductance and forms one of the filter coils of the power supply.

The possible efficiency of a speaker of this type is much better than the rocking-armature type described above, and it has a much greater possible output. Thus one of the better commercial types is said by the manufacturer to have an average efficiency of 25 per cent, with a possible power input of 10 watts. Its efficiency is probably somewhat less than 10 per cent; even this low value makes it considerably better than the cone with the rocking-armature motor. The possible motion of the cone, which is attained only at the very low frequencies, is about $\frac{1}{16}$ inch.

The field coil uses about 10 watts of power for its excitation. As the moving coil has a resistance of only about 10 ohms, and, as the speaker impedance should match that of the tube from which its power is supplied, the moving coil must be connected to the plate circuit of its tube by a transformer. If one having a turn ratio of 30 to 1 is used the 10 ohms of the coil will appear as 9000 ohms in the primary coil and this is about right for the tube from which the speaker's power comes.

7. Measurement of Amplification—Transmission Limit.—It has been customary in radio literature to speak of amplification in terms of voltage; for example, if one stage of audio frequency amplification gives a voltage ratio, output to input, of 24, the circuit is said to give a voltage amplification of 24. Of this, probably eight-fold amplification has been obtained in the triode itself and three in the transformer used with the triode.

The only real amplification is that in the triode; here a small

input power controls a large output power and so we have a real *amplification of power*. In the transformer the voltage of the signal is changed but there is no amplification of power; on the contrary there is a loss of power in the transformer.

It is becoming customary in radio literature to measure all amplification from the standpoint of power, and the radio art has adopted the system of the telephone art, in measuring the amplification.

For reasons not worth while discussing here the telephone engineer employs as the unit of power amplification the *transmission unit*, abbreviated T.U. This unit is defined by means of an equation which seems involved at first; the use of the unit is not as difficult as the definition would indicate.

Let P_1 be the power before amplification.

P_2 be the power after amplification.

Then,

$$\text{Number of T.U. of amplification} = 10 \log_{10} \frac{P_2}{P_1}. \quad . \quad (59)$$

Thus if the power output is 100 times the power input

$$\text{T.U.} = 10 \log_{10} \tfrac{100}{1} = 10 \times 2 = 20.$$

So if the power is increased 100 times the power amplification is 20 transmission units or 20 T.U. And if the power is increased 1000 times

$$\text{T.U.} = 10 \times \log_{10} \tfrac{1000}{1}, = 10 \times 3 = 30.$$

If the power is doubled the amplification

$$\text{Number of T.U.} = 10 \log_{10} 2 = 3.01.$$

If the power is increased 26 per cent then the amplification

$$\text{Number T.U.} = 10 \log_{10} 1.26 = 1.$$

The power ratio and corresponding number of transmission units of amplification are given in the table on page 220.

Just as this book is going to press there has been adopted a new name for the transmission unit, namely the *decibel*. The *bel* part of the name comes from the name of Bell, inventor of the telephone, and the prefix indicates that the unit is one-tenth of the bel. It is abbreviated *db*.

No. T. U.	Power Ratio	No. T. U.	Power Ratio	No. T. U.	Power Ratio	No. T. U.	Power Ratio
0.1	1.023	1.2	1.318	3.5	2.24	8.5	7.08
0.2	1.047	1.4	1.380	4.0	2.51	9.0	7.94
0.3	1.072	1.6	1.445	4.5	2.82	9.5	8.91
0.4	1.096	1.8	1.514	5.0	3.16	10.0	10
0.5	1.112	2.0	1.585	5.5	3.55	20.0	100
0.6	1.148	2.2	1.660	6.0	3.98	30.0	1,000
0.7	1.175	2.4	1.738	6.5	4.47	40.0	10,000
0.8	1.202	2.6	1.820	7.0	5.01	50.0	100,000
0.9	1.230	2.8	1.906	7.5	5.62		
1.0	1.259	3.0	1.995	8.0	6.31		

8. Radio-frequency Amplification.—All radio broadcasting stations carry the same audio frequencies, namely, all the frequencies in the audible range. These frequencies are carried as modulations of the radio frequency which the station is sending out; the audio frequencies are not actually present as such but are obtained from the modulation after the detector has functioned.

The only means of selecting one station from another depends upon the different radio frequencies sent out and so it follows at once that any selection between stations must be made *before the radio frequency is eliminated by the detector action.*

With coils having a power factor of about 1 per cent, as is the case with the average radio receiver, one tuned circuit will not give sufficient selectivity to eliminate interference with the broadcasting channels crowded as they are today. It requires at least three tuned circuits, in cascade, to give the required selectivity.

The ordinary arrangement of these three circuits is shown in Fig. 145. The antenna circuit is generally not tuned (although a few radio receivers do have tuning means for this circuit). It is coupled tightly to the tuned input circuit of the first R.F. triode. The second tuned circuit is the input circuit of the second R.F. triode, which is coupled about 50 per cent to the plate coil of triode 1. The third tuned circuit in the input circuit of the detector, coupled to the output circuit of the second R.F. triode. For the broadcast frequencies the coils L_1, L_2 and L_3 are each about $200\mu h$, requiring that the tuning condensers have a capacity of about $0.0003\mu f$. These condensers are all arranged in the same shaft or are coupled mechanically in some way, for operation from

a common control. The antenna coil and the plate circuit coils have about $10\mu h$ or less, generally wound with fine wire. Their resistance plays only a very minor role in the tuning of the set and the fine wire offers some advantages, mechanical and electrical, over a normal sized wire.

9. Difficulty in Radio-frequency Amplification.—The circuit of Fig. 145 does not operate as well on the set as the simple foregoing analysis would indicate. There is a very strong tendency for the triodes to set up oscillations in the tuned circuits, so strong, as a matter of fact, that unless special precautions are taken to prevent them the oscillations will be so violent as practically to paralyze the amplifier; it is "dead" in so far as amplifying some incoming signal is concerned.

There are two factors which contribute to the setting up of these

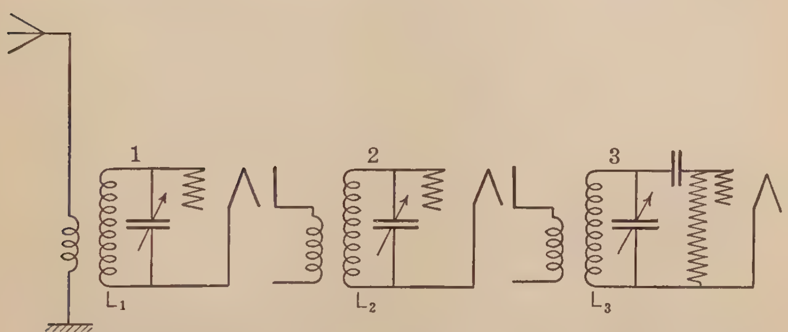

Fig. 145.—Ordinary arrangement of tuned radio-frequency amplifier.

oscillations, the magnetic and capacitive coupling from one tuned circuit to another, due to their arrangement and proximity, and the *capacity between the grid and plate of the triodes themselves.*

The magnetic coupling between the coils of the several tuned circuits can be effectually eliminated by either of the arrangements indicated in Fig. 146. In the scheme shown in (*a*) the three coils, of approximately the form shown, can be arranged to have zero mutual inductance if their axes are placed at an angle of about 58° to the common base line. The exact angle will depend upon the form of coil used.

In the arrangement shown in (*b*) the three coils have their axes respectively at 90° to each other. Neither of these arrangements will eliminate the electric (capacitive) coupling between the differ-

ent circuits. One method of eliminating this, at the same time as the magnetic coupling is eliminated without either of the schemes shown in Fig. 146, is to enclose the coils entirely in individual,

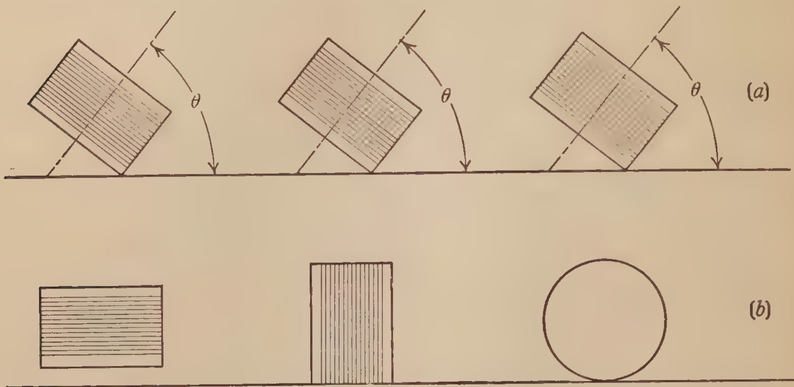

FIG. 146.—Two arrangements for eliminating mutual induction between three coils placed close to one another.

grounded, copper cans. These cans must not fit too closely around the coils as they would spoil the tuning qualities of the circuit if they did.

10. Neutralization of Inter-electrode Capacitive Coupling.—The inter-electrode (grid to plate) capacity of the triode itself is more important than either of the other two effects mentioned above. This capacity is about $10\mu\mu f$ in the average triode, not much, to be sure, but sufficient to render the amplifier useless unless properly guarded against. This capacity permits the plate circuit to induce a voltage back into the grid circuit and such a regenerative feed-back may cause oscillations, as analyzed in Chapter IV.

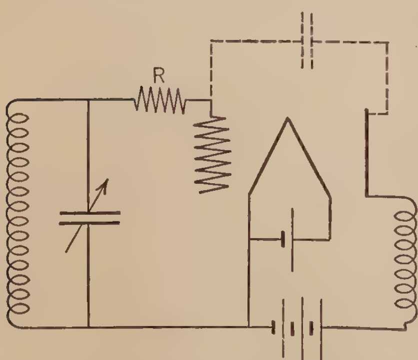

FIG. 147.—One method of discouraging undesired oscillations due to grid-plate capacitive feed back.

One method of nullifying the action of this feed-back path is to insert in series with the grid of each tube a high resistance, say

1000 ohms or more. In Fig. 147 the grid to plate capacity of the triode is shown by the dotted lines; in series with the grid the resistance R has been inserted and it is seen that any energy which the plate sends to the grid circuit must flow through this resistance. The resistance is not in series with the tuned circuit, it will be noticed, and so has no appreciable effect on either the tuning of the receiver or its response to signals.

In another stabilizing scheme which has been used the normal potential of the grid is adjustable by a potentiometer connection to the filament circuit battery; by adjusting the potentiometer to make the grid somewhat positive, with respect to the negative end of the filament, the effective resistance of the tuned circuit is increased to such an extent as to inhibit the oscillations. The potential of the grid should be manually adjustable if best results are to be obtained; the tendency to oscillate is much greater when the tuned circuit is adjusted for high frequency than for the lower, so the potential of the grid should be correspondingly altered.

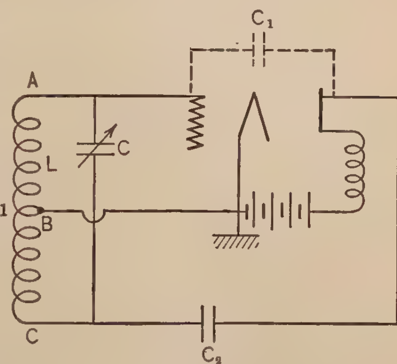

FIG. 148.—One circuit arrangement for neutralizing capacitive feed back.

The scheme most generally used is to use an additional small condenser, suitably connected, so that *two equal and opposite voltages* are set up in the grid circuit when the plate voltage fluctuates. One scheme is shown in Fig. 148; the tuning coil L is tapped for the filament connection at its mid-point. The small condenser C_2 has the same capacity as the condenser C_1, the capacity between grid and plate of the triode.

When the plate fluctuates in voltage it induces one voltage into the grid circuit through condenser C_1 and another equal voltage through C_2. These two voltages tend to set up currents in the oscillatory circuit L–C in opposite directions; these two effects being equal to each other, no current at all is set up.

In case point B is not at the middle of the coil L the capacity of C_2 must be different from that of C_1; the fewer the turns between B and C, the larger must C_2 be.

In another scheme, slightly different in arrangement but having the same action as that described for Fig. 148, there is an auxiliary coil added to the plate coil, as shown in Fig. 149. The normal plate coil A–B is extended by the section B–C, this being a continuation

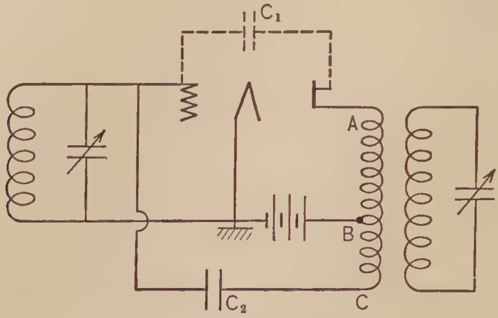

FIG. 149.—A slight modification of the arrangement of Fig. 148, to accomplish the same purpose.

of the winding A–B. The coil B–C is preferably coupled very tightly to the coil A–B. The condenser C_2 is added also to the normal circuit; the size of this condenser is so chosen that its capacity multiplied by the number of turns in B–C is equal to the product of the capacity of C_1 multiplied by the number of turns in A–B. As actually carried out, this relation is satisfied by making

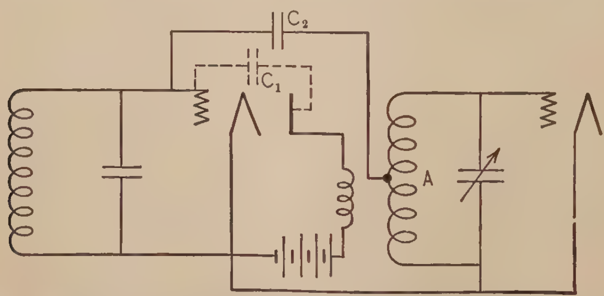

FIG. 150.—With tight coupling between coil A and its associated plate coil, this scheme may be used for neutralizing the effect of grid-plate feed back.

the neutralizing condenser adjustable; after the set is assembled the neutralizing condenser is set at that value, which prevents oscillations. Either too large or too small a value of C_2 permits the setting up of oscillations; the proper value is found by trial.

Still another form of circuit for neutralizing the effect of the inherent capacity C_1 is shown in Fig. 150. Here the extra, neutralizing, condenser C_2 is connected between the grid and a point of the coil in the tuned circuit coupled to the plate coil. The point in this coil is so chosen with relation to the capacity of C_2 that the voltage induced into the grid circuit through condenser C_2 is just equal and opposite to that induced into it through the inter-electrode capacity C_1. The arrangement of a commercial form of neutralized, two-stage radio frequency amplifier is shown in Fig.

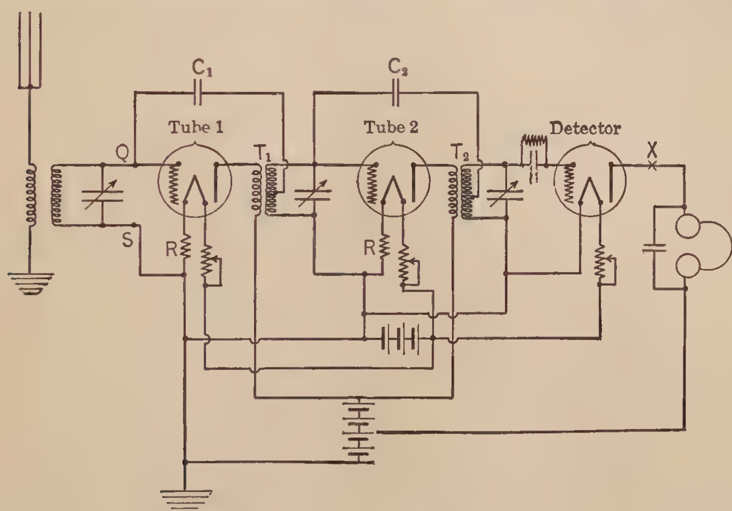

Fig. 151.—Circuit arrangement of a neutralized radio-frequency amplifier.

151. Of course, all three tuning condensers are adjusted by a single control.

Sometimes regeneration may be used in the second stage of a two-stage neutralizing amplifier; thus the arrangement of Fig. 151 might have a tickler coil inserted at the point X and the coil be magnetically coupled to the secondary coil of the radio-frequency transformer T_2.

Such use of regeneration is not subject to the same objection as that made when discussing Fig. 140, p. 210. If the circuit of this figure should be made to oscillate, due to too much tickler coupling, all the neighboring listeners would be bothered by the whistling note there mentioned, as the antenna would radiate high-frequency power. But if the arrangement of Fig. 151 should

oscillate no trouble would be caused the neighbors because the oscillations would be set up in the secondary circuit of transformer T_2, and, because of the two neutralized stages between this and the antenna, no radio-frequency disturbance could find its way back into the antenna circuit.

11. The Super-heterodyne, or Double-detection, Receiver.—In another type of radio-frequency amplifier the radio-frequency current is brought down to audio-frequency current in two steps, instead of one. As evident from the above discussions it is not easy to construct a good radio-frequency amplifier for say 1000 kc., but the same instability does not exist in an amplifier designed for 50-kc. current. The tendency to self-oscillation decreases as the frequency for which the circuit is tuned becomes lower. Thus if the broadcast frequencies were as low as 50 kc. very little trouble would be experienced from the tendency of the tuned circuits to oscillate as a result of the inter-electrode capacity of the triodes. The super-heterodyne receiver takes advantage of this fact by first reducing the broadcast frequency, of approximately 1000 kc., to a much lower one, say 50 kc., amplifying the lower frequency current in several tuned stages, and then reducing this frequency to the audible range. This scheme evidently requires two detector tubes, one to reduce the 1000 kc. to 50 kc. and another to reduce the 50 kc. to audible frequencies. This accounts for the name *double-detection* receiver.

One arrangement of the circuits is as shown in Fig. 152. The first tube is a self-oscillating one, in which the frequency of oscillations are controlled by condenser C_1. The output of this oscillating detector is supplied to the intermediate frequency amplifier which is of the tuned type. Whereas the diagram shows the primary circuits of the intermediate frequency (I.F.) transformers tuned, better results are generally obtained by tuning the secondaries instead.

The frequency of the oscillating detector is so adjusted as to give, with the carrier wave of the desired signal, a beat frequency equal to that for which the I.F. transformers are tuned. Signals differing from the desired one by 10 kc. will then give a beat note either 10 kc. higher or 10 kc. lower than this, and the I.F. amplifier will not appreciably amplify a frequency differing this much from its normal frequency, hence these other signals give no interference with the desired signal

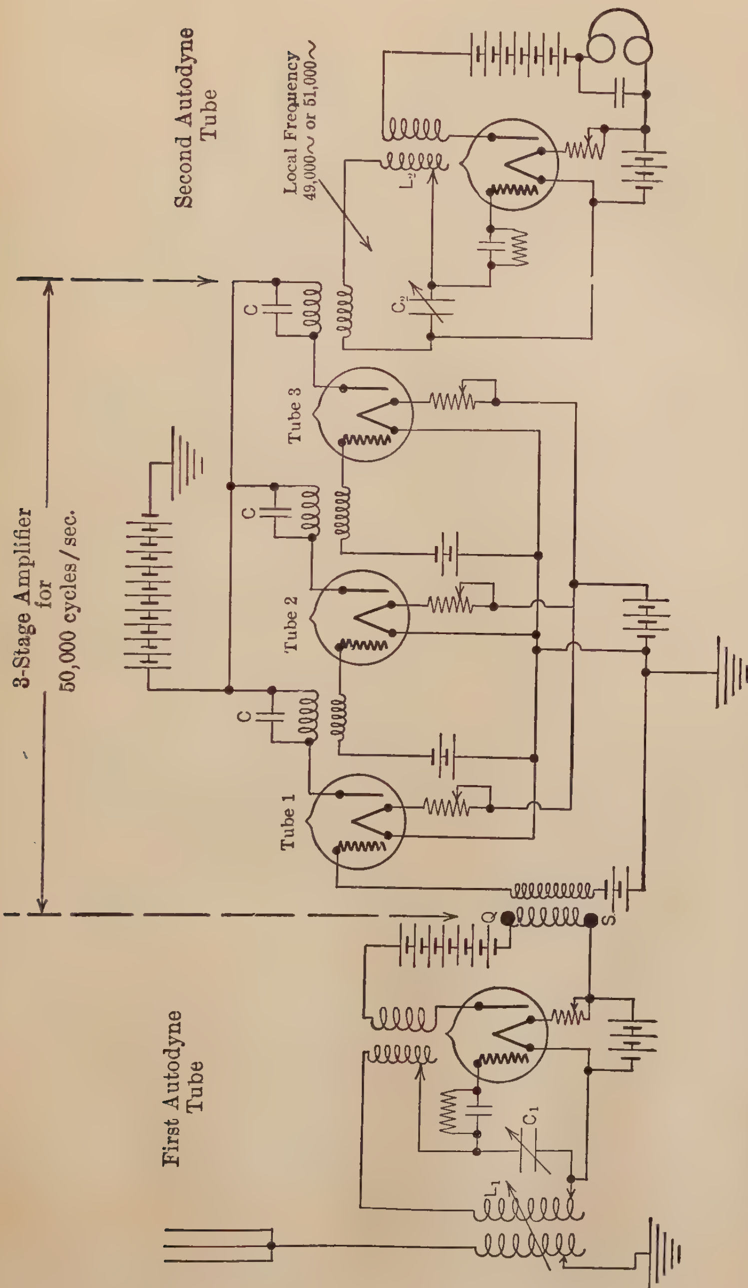

FIG. 152.—The double-detection, or superheterodyne receiver. The intermediate-frequency amplifier is tuned broadly so as to transmit a frequency band about 10 kc. wide. The transformers are here shown with tuned primary circuits; generally the secondary circuits are tuned.

The output of the I.F. amplifier is supplied to another tube, used as detector; if continuous-wave telegraphy is being received this last tube will be an oscillating one, generating such a frequency as will, when combined with that coming through the I.F. amplifier, give an audible beat note.

In case a radio-telephone signal is being received the last detector tube should not be an oscillator; the modulation which was carried by the signal wave is passed along to the I.F. current and so carried through the I.F. amplifier. The detector action of the last tube then removes the 50-kc. current leaving for the phones the modulation frequency of the received signal.

The I.F. amplifier must have quite definite frequency-amplification characteristics if the receiver is to work well. It should amplify equally well a band of frequencies about 8 kc. wide, outside this frequency band it should not amplify at all.

12. Action of the Super-heterodyne Receiver.—Suppose the circuit is as shown in Fig. 152, the I.F. amplifier being resonant at 50 kc. If a signal of 1000 kc. carrier is being received the first oscillating detector would be made to oscillate at either 950 kc. or 1050 kc.; either of these, beating with the 1000-kc. carrier, would give a beat frequency of 50 kc., which is then " detected " and supplied to the " input " of the I.F. amplifier.

The voice modulation, which was being carried by the varying amplitude of the 1000-kc. wave, will be automatically passed along to the 50-kc. carrier, so that going through the I.F. amplifier there is a voice-modulated 50-kc. current, that is, a 50-kc. carrier with side bands, these being of the same frequency width as they were on the signal current.

If the I.F. amplifier is too sharply tuned the upper parts of the side bands (that is, the consonants) are eliminated and the reproduction is drummy. And if the tuning of the I.F. amplifier is too broad it will send through the beat frequencies produced by the local oscillator and some undesired signal, giving say a beat frequency of 40 kc. or 60 kc.

There are two disadvantages to the ordinary super-heterodyne receiver, which could, however, be easily remedied. For a given signal there are *two settings* of C_1 which serve equally well to bring in the desired signal; and next, for any setting there are *two signals* (the desired one and another) which give the same beat frequency and hence amplify equally well in the I.F. amplifier. By

utilizing suitable filter circuits both of these defects can be overcome.

13. Super-heterodyne and Broadcast Receiver for Short Waves.—Many of the broadcasting stations now send out their programs on short waves, as well as on one of the normal broadcasting channels; these short-wave transmissions are generally from 20 to 50 meters, that is, from 15,000 kc. to 5000 kc. Of course the ordinary broadcast receiver could not possibly pick up these signals, as the highest frequency the ordinary broadcast receiver will tune in is about 1500 kc.

It is quite possible, however, to use the broadcast receiver as an intermediate frequency amplifier, for receiving these short waves, by using an arrangement similar to that shown in Fig. 152, with the addition of a by-pass condenser around the coil QS. An additional tube and associated apparatus is required, arranged as shown in Fig. 152 for the "First autodyne tube." That is, a triode arranged with tickler to produce oscillations, of nearly the same frequency as the short waves to be received, is arranged to feed the "Input" terminals of the ordinary broadcast receiver.

We will analyze the action by supposing the broadcast receiver is tuned for 1000 kc. (300 meters) and left at this setting, and that the signal to be received is a voice modulated 15,000-kc. wave. The antenna, which must be a short one, is tuned for 15,000 kc. The additional circuit (first autodyne tube of Fig. 152) is set into oscillation by suitable adjustment of its tickler coil, and the condenser C_1 is set to produce oscillations of 14,000 kc. There is then impressed on the grid of this first tube the combination of a 14,000-kc. constant amplitude wave, and a 15,000-kc. voice modulated wave. The resulting "beat" of 1000 kc. is "detected" by the action of the grid condenser and grid leak, so that flowing through the coil QS there is a frequency of 1000 kc., modulated by the same voice wave as modulated the 15,000-kc. wave. Now the broadcast receiver is adjusted to amplify a current of 1000 kc.; so from here on the broadcast receiver functions as it does in ordinary broadcast reception.

To receive the short waves the circuit of the first autodyne tube of Fig. 152 must be properly designed. The coil QS may be the antenna coil of the broadcast receiver itself, that is, the posts S and Q are the "ground" and "antenna" posts of the broadcast receiver. The other coils in the circuit must be suitable for the

high frequencies to be generated, having an inductance of about $10\mu h$ each. The condenser C_1 should have a maximum capacity of about $0.0001\mu f$. The coil QS should be shunted by a condenser of about $0.0005\ \mu f$.

In this scheme of reception, the "Second autodyne tube" of Fig. 152 is not arranged to oscillate; it is the detector tube of the broadcast receiver; and its plate circuit, instead of actuating the telephone receiver, as shown in Fig. 152, feeds into the audio-frequency amplifier.

14. Selectivity of Receivers and Effect on Quality.—The radio-frequency amplifying circuits of the broadcast receiver are put in for the double purpose of amplifying the desired signal and selecting this signal from others. The tuned circuits naturally amplify best the frequency for which they are tuned; frequencies differing from the tuned frequency are amplified less as they differ more from the tuned frequency. This follows from the form of the resonance curve (see Fig. 22, p. 51).

If we then take as unity the amount of amplification of the desired frequency, namely, that for which the circuit is tuned, all other frequencies are amplified less than unity; the engineer says they are so many T.U.'s "down."

If for example the power of the tuned frequency is increased 10,000 times this amount of amplification is taken as unity. Suppose a frequency differing 5 kc. from the tuned frequency is amplified only 100 times then its amplified power is only 1/100 as much as the tuned frequency. Referring to the T.U. table (p. 220) we see that a power ratio of 100 is equal to 20 T.U.'s so that this frequency, 5 kc. off resonance, is 20 T.U.'s down. Suppose that a frequency 10 kc. off resonance has its power amplified only 10 times; its power would be only 1/1000 that of the tuned frequency and it would be 30 T.U.'s down.

The selectivity characteristic of a receiver is therefore given by plotting its power amplification for various frequencies differing from the tuned frequency. Naturally a set having three tuned stages is more selective than one having only one tuned stage; a regenerative single circuit set is more selective than a non-regenerative single circuit set, etc. In Fig. 153 are given the experimentally determined selectivity curves of several of the different types of receivers, the tuned frequency for all sets being the same, namely, 900 kc.

If we assume that the range of frequencies required for accurate speech and orchestral reproductions is 10,000 cycles, the ideal receiver would show the same amplification for all frequencies in this range. Thus the carrier and all frequencies in the band from 10 kc. higher to 10 kc. lower would be amplified alike. And of course all frequencies outside this band should not be amplified at all, so as to eliminate interference. Such a selectivity is ideal;

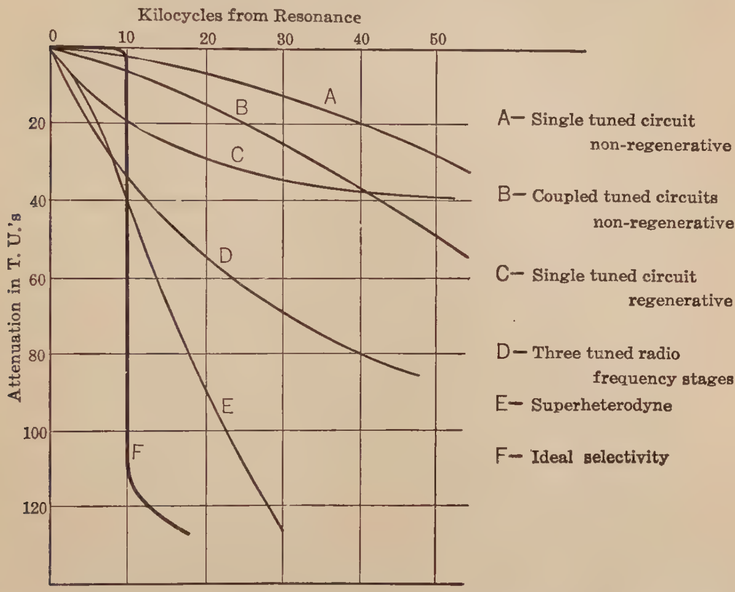

FIG. 153.—Experimentally determined selectivity curves for various types of radio receivers, together with an ideal selectivity curve.

the power amplification of such a receiver is shown in Fig. 153, and labeled "ideal selectivity."

These curves show how bad the performance of the average broadcast receiver really is. The single-circuit non-regenerative set gives practically the same amplification over the 10 kc. band, but is very broad in its tuning and so permits other signals, even 60 kc. different from the desired signal, to interfere seriously.

The most selective receiver is the super-heterodyne; this is so selective that it cuts off practically all of the higher frequencies in the audible range. As power varies with the square of the current, it can be seen that a power ratio of 20 T.U.'s means a current ratio

of 10 to 1. From the curve of Fig. 153, then, it can be seen that the super-heterodyne receiver, and those using two or three stages of R.F. amplification, will amplify a 905-kc. current only 10 per cent as much as they will the 900-kc. current. This means that voice frequencies of 5000 vibrations a second, the consonant sounds, come through such a receiver with only 10 per cent as much amplification in current, or only 1 per cent as much amplification in power, as the low-voice frequencies, that is, the vowel sounds.

It is because of this characteristic that speech from a radio receiver is less distinct than the original; as a woman's voice is higher pitched than a man's this action of the tuned circuits is more serious in rendering indistinct a woman's voice than a man's. Roughly the consonants of a man's voice extend into the frequency range 3000 to 6000, while those of a woman's voice reach

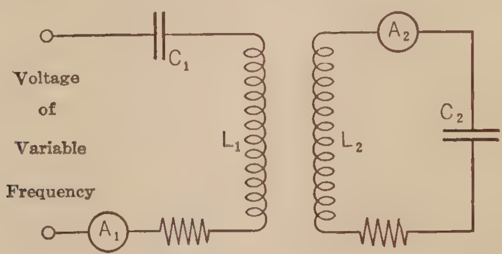

FIG. 154.—A pair of coupled tuned circuits.

as high as 6000 to 8000. To offset this serious defect of the ordinary receiver attempts are now being made to shape the receiver's selectivity curve more in accordance with that curve of Fig. 153 labeled "Ideal selectivity."

15. Use of Coupled Tuned Circuits between Triodes.—It was shown in Chapter II that if a coil in series with a condenser has impressed a voltage fixed in magnitude but variable in frequency, the current varies in magnitude with frequency, being a maximum when the frequency is such as to make the inductive reactance equal to the capacitive reactance. Plotting the different values of current against the corresponding frequencies gives the well-known resonance curve, one of which is given in Fig. 22, p. 51.

If now two tuned circuits are coupled together magnetically as indicated in Fig. 154 and a variable frequency voltage is impressed upon one of them the resonance curve obtained is peculiar in form.

The resonance curve, for both circuits, shows two resonance "humps," as indicated in Fig. 155. In this figure the form of primary current (the L_1–C_1 circuit of Fig. 154) is shown in full lines and the current in the secondary circuit is shown by the dashed curve.

If now the two coils L_1 and L_2 of Fig. 154 are moved farther apart, so that the mutual induction between them is less, and the resonance curves are again obtained they will look like those given in Fig. 156. The two resonance humps have moved closer together,

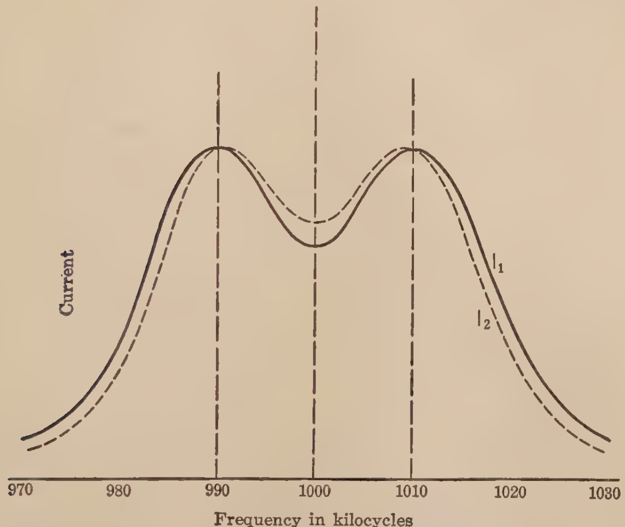

FIG. 155.—Resonance curve for the primary circuit of Fig. 154; the secondary current is closely proportional to the primary current.

and in the secondary circuit have actually merged together to give one resonance hump, somewhat flatter than the resonance hump of a single resonant circuit.

Now a resonance curve of this form is exactly what is wanted in the radio frequency amplifier of a radio receiver. If the resonance hump extends, practically flat, for about 5 kc. either side of the carrier frequency, then the consonants and high musical notes are not discriminated against as they are in the ordinary receiver, as shown in Fig. 153. Some modern receivers are using this scheme to give more nearly uniform amplification, in the R.F. stages, of all the voice frequencies. One form of the idea is shown in Fig. 157;

the coupling between the coils of the R.F. transformers is rather weak, about 1 per cent. This means that the mutual inductance M, between the two coils of the transformer L_1 and L_2 is given by the relation

$$M = 0.01\sqrt{L_1L_2}.$$

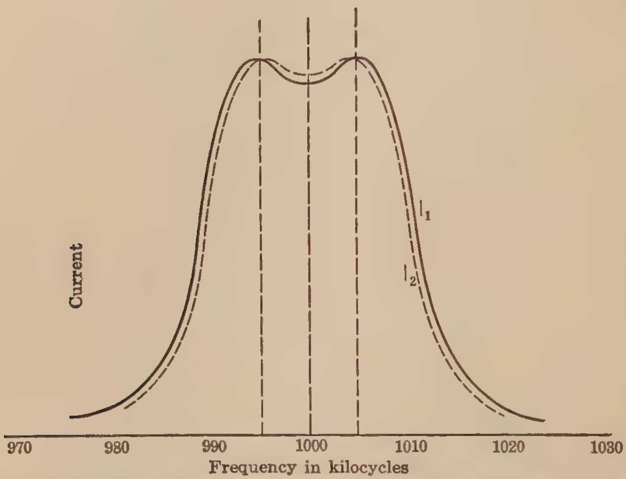

FIG. 156.—With looser coupling the two "resonance humps" of Fig. 155 move closer together.

The value of M should be variable over the broadcast range to give the same selectivity for long as for the short waves. For the 600-kc. setting the coupling between L_1 and L_2 should be two and one-half times as much as it is for the 1,500-kc. setting. Obviously

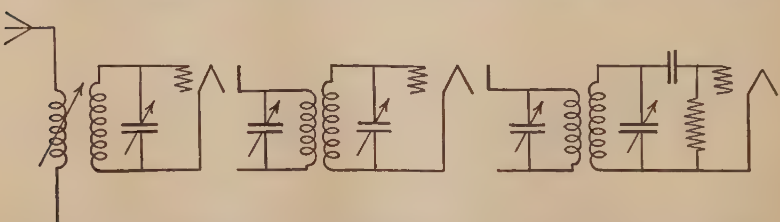

FIG. 157.—A radio-frequency amplifier having "band selectivity"; it utilizes the idea of Fig. 156.

the same mechanical movement which adjusts the setting of the condensers can also be used to bring about this change in M. Of course capacitive coupling of the two circuits can also be employed;

in this case the coupling condensers of suitably shaped plates can be mounted on the same shaft as the tuning condensers; all of these must be on the same shaft as otherwise the adjustment of the set is too laborious an operation.

16. Overloading the Detector Tube Causes Distortion.—After the signal has been brought through the radio-frequency amplifier without distortion (all frequencies amplified equally well) it may still be spoiled either by the action of the detector tube or by the audio-frequency amplifier. The detector tube will very seriously distort the signal if the radio-frequency signal impressed on its grid circuit is too strong; the R.F. signal should not be more than about one volt in amplitude, unless some special arrangement has been made to avoid distortion.

The detector is normally arranged with a grid condenser and leak, between the tuned input circuit and the grid, and about 22 volts is used in the plate circuit. It is for this arrangement that the limit of about one volt signal applies. If plate-circuit detection is used, there being no condenser in series with the grid, and 45 volts are used in the plate circuit, the signal may be several times as strong without bringing in severe distortion. Of course such an arrangement of the detector tube is not as efficient (as detector) as the normal arrangement.

17. Requirements for Good Audio-frequency Amplification.—In receiving a radio-telegraph signal, the requirements of the A.F. amplifier are very simple; only one musical note is to be amplified, and is generally of about 800–1000 vibrations per second. Even poorly designed transformers and circuits will amplify such a signal very well; if a transformer is used to repeat the signal from one triode to the next it may have a step-up ratio as high as 6 to 1, giving a voltage ratio per stage (triode plus transformer) as high as 50. This is the same as about 35 T.U.'s gain per stage.

To amplify the voice, or orchestral selections, with fidelity is a much different task. To preserve the natural quality of the voice the amplifier should respond equally (give the same amplification) to all frequencies from 100 to 8000, and to preserve the quality of organ selections the amplifier must perform as well for a 50-vibration per second note as it does for any other. There are very few radio sets, even today, which give the proper reproduction of an organ program, and very few of them give the consonants of the voice in their proper relative intensities.

If there is much interference from other broadcast channels, it may be advisable to have the audio-frequency amplifier "cut off" at about 4000 cycles; the effect on the fidelity of speech is not very marked, and much interference is eliminated.

18. Types of Audio-frequency Amplifiers.—Audio-frequency amplifiers are classified according to the kind of circuit used to take

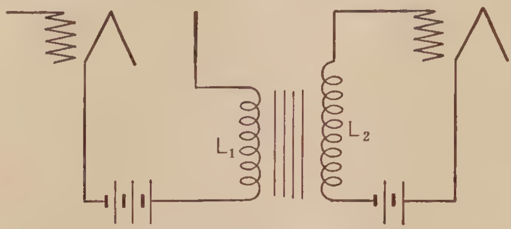

Fig. 158.—Transformer repeating amplifier.

the power from the plate circuit of one triode and use this power to energize the grid of the next one. Probably 95 per cent of the A.F. amplifiers today utilize an iron-core transformer, having its primary in the plate circuit of one triode and its secondary between the filament and grid of the next triode, as indicated in Fig. 158. This is called a " transformer repeating " amplifier.

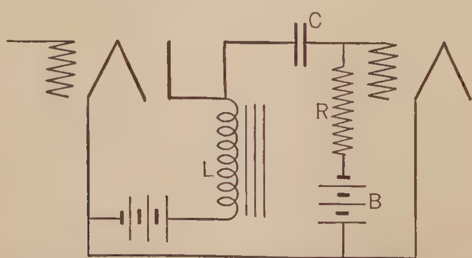

Fig. 159.—Choke coil repeating amplifier, or inductance repeating.

In another type an iron core coil is used in the plate circuit and the reactance drop across this coil, produced by the fluctuating plate current, is repeated to the next input circuit by means of a condenser C, as shown in Fig. 159. To maintain the grid at a suitable negative potential a small battery B is used in series with the grid leak R. In a modification of this scheme, shown in Fig. 160, the grid leak resistance R of Fig. 159 is replaced by an iron-core induct-

ance L_2. The L_2–C circuit may be made to have a resonant frequency in the region of 50 cycles per second, and this condition will help the amplifier to care for the lower audio frequencies, say from 100 down to 50. Because of the iron core, and the fine wire

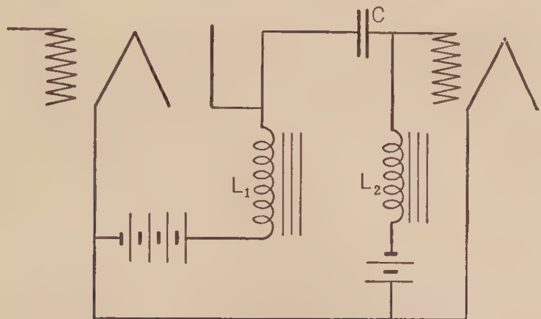

FIG. 160.—Inductance repeating amplifier, with inductive grid leak.

used in the construction of coil L_2, the resonance of the L_2–C circuit is rather flat, a condition desirable in this case. The coils of Fig. 159 and both coils of Fig. 160 should each have at least 50 henrys of inductance; in the case of L_1 and L this inductance of 50 henrys is to be the value offered to a weak signal, when the plate

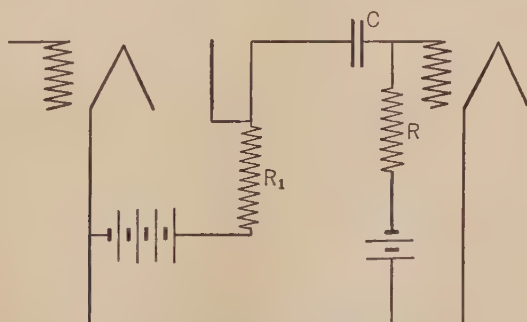

FIG. 161.—Resistance repeating amplifier.

current is flowing through the coil and so giving the core some average value of flux density, about which value the fluctuation in the plate current (i.e., the signal current) makes it vary.

In still another type of repeating circuit the coil of Fig. 159 is replaced by a resistance of suitable value; this is called a resistance repeating amplifier and is shown in Fig. 161. The resistance R_1

should be about twice the alternating-current resistance of the plate circuit of the triode; in other words, it should be about equal to the continuous-current resistance of this circuit. The leak resistance should have about ten times the resistance of R_1 and the condenser C should have a reactance, for the lowest frequency to be repeated, low compared to the resistance R.

19. Relative Merits of the Different Types of Amplifiers.—A properly proportioned resistance-coupled amplifier gives less signal distortion than either one of the others, as ordinarily built. However the amount of B battery required is twice as much as either of the others, and the amount of voltage amplification per stage is about 70 per cent as much as can be obtained from the inductance-repeating type and about one-fifth as much as is obtained from the transformer type. At the lower frequencies, say below 100 cycles, the inductance-repeating type with the inductive grid leak gives two or three times as much amplification as does the resistance-coupled type.

Because they have the same defects (as regards distortion) as the transformer type and as they give much less amplification than the transformer type, and because they do not give as faithful a reproduction as the resistance type, the inductance-repeating type is seldom used. Because it gives so much greater a voltage amplification with less battery consumption the transformer type is nearly always preferred to the resistance-coupled type.

20. Proper Design of Audio-frequency Transformers.—The iron used for the cores should have as high a permeability as possible, and low losses. The high permeability must exist for the comparatively low voltages which the signal usually impresses on the transformer; thus the transformer in the plate circuit of the detector seldom has a signal voltage in excess of one volt. The primary inductance is about 50 henrys, so at 100 cycles the coil has about 30,000 ohms reactance. Its effective resistance will be about 10,000 ohms, so the impedance will be about 31,000 ohms and the current (alternating) for a signal of 1 volt will be about 30 microamperes. As the primary coil has about 6000 turns this current represents a magnetizing force of $6000 \times 30 \times 10^{-6} = 0.18$ ampere turn. And as the magnetic circuit is about 20 cm. long the magnetizing force is about 0.01 ampere turn per centimeter.

Now for such a low magnetizing force ordinary "electric steel" has a permeability of a few hundred; the iron used in the best

transformers today has a permeability, however, for these low magnetizing forces, of 500–1000.

The reactance of the primary coil, for the lowest frequency to be amplified, must be high compared to the resistance of the plate circuit of the triode. As this is generally about 10,000 ohms for the ordinary amplifying tube, and the transformer should repeat frequencies at least as low as 50 cycles, this makes advisable an inductance of between 50 and 75 henrys.

If the transformer is to have a step-up ratio of three (about as

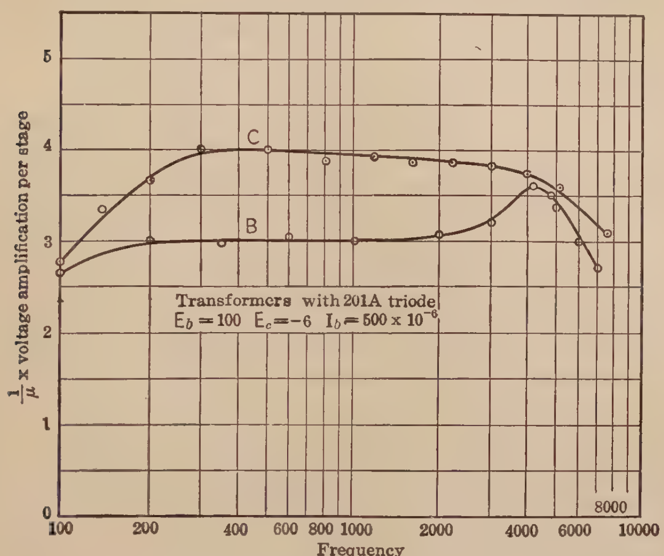

FIG. 162.—Amplification characteristics of two of the better types of commercial transformers.

much as is feasible) the secondary inductance will be about 500 henrys. With a leakage reactance of 10 per cent, and a total capacity connected to the secondary (internal and external) of 15 micro-microfarads, the secondary circuit will show resonance at about 6000 cycles. The resonance is not very sharp because of the high resistance of the secondary winding.

The amplification of two of the better types of commercial transformers is shown in Fig. 162; there are others available considerably better than this, and there are a great many poorer. The resonance peak in one of the transformers occurs at 4000

cycles and it is evident from the form of this curve that an A.F. transformer will not repeat frequencies much higher than its resonance frequency.

By putting a copper band around the secondary winding the resonance peak is partly eliminated and is moved to a slightly higher frequency.

A transformer built with better iron, and having its winding arranged in sections to cut down the internal capacity, shows a resonance peak as high as 7000 cycles, and holds up its amplification much better in the lower frequency range. The curves given in Fig. 162 are for the transformer only; the "voltage amplification per stage" has been divided by μ, the amplification factor of the tube.

21. Methods for Controlling Signal Strength.—As the user of a radio receiver tunes in different stations he must have some convenient method of regulating the amount of power supplied to the loud speaker. It may be that some distant station requires the full amplification of the set and that a nearby station requires only 1 per cent of the possible amplification to furnish to the loud speaker all the power it can use, without distortion.

Three of the possible methods are: control of filament current of the amplifier tubes, mistuning, and some shunt method.

Mistuning is a perfectly good method when there are no interfering stations sending on channels close to that of the desired station. It is unsatisfactory when interfering stations are to be considered, because by mistuning the desired signal is weakened and the signal from one of the undesired stations is actually strengthened.

Controlling signal strength by adjusting the filament current of some or all of the amplifying tubes has been extensively used. It is a convenient method and, as long as the signal is weak, no disturbing effect on the quality of the signal is noticed. But as the signal proceeds through the various stages of the amplifier it increases in intensity and by the time it reaches the audio-frequency amplifier stages it is generally measured in volts. For strong signals filament control should never be used to adjust signal strength; distortion is sure to occur. If, then, filament control of signal strength is to be used it should be used *only on the radio-frequency amplifier tubes;* the audio-frequency tubes should have their full-rated filament current for all signals.

The best method of signal control is to use full normal filament current for all tubes, and have a variable shunt path somewhere in the amplifier to divert the undesired fraction of the amplified signal. A convenient method is shown in Fig. 163, which indicates an arrangement of the output circuit of one of the radio-frequency amplifier tubes, generally the one feeding the detector. The primary coil of the R.F. transformer is shunted by a resistance R, which has a sliding contact A, connecting to the plate of the triode. If A is moved to the lower end of R no signal is transmitted, and if A is at the top of R practically full signal is transmitted, if R is of sufficiently high resistance.

In some schemes a variable resistance has been shunted across

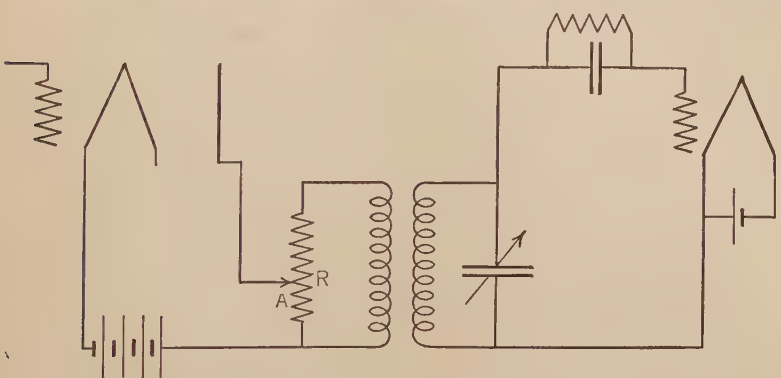

FIG. 163.—One method of controlling the signal strength.

one of the coils of the R.F. amplifier; such a scheme results in a certain amount of mistuning which is not present to the same degree in the fixed resistance shunt of Fig. 163.

22. Proper Output Tube.—In the older designs of amplifiers the same type of tube was used in all stages but no modern broadcast receiver follows this practice.

The normal amplifier tube draws a current of about 1 milliampere, at say 90 volts. This gives an input to the plate circuit of 90 milliwatts. The output to the loud speaker should not exceed about 10 per cent of the input to the plate circuit, or the discerning ear will find signal distortion. The fraction 10 per cent of course depends upon the quality of signal desired by the listener; in general it may be stated that the smaller the output the less is the signal distortion.

The modern loud speaker requires about 100 milliwatts of power to give a signal suitable for ordinary purposes and the tube feeding the loud speaker must be able to deliver at least ten times the average power, during emphasized passages. In fact, the modern *dynamic* speaker as it is used frequently for demonstration purposes is taking power measured in watts, instead of milliwatts.

If a speaker is to use 100 milliwatts on the average, and peak powers at least 10 times this amount, the output tube should be drawing from its battery at least 10 watts of power. Thus the output tube if connected to a 300-volt power supply for its plate circuit should be drawing about 50 milliamperes of current. This would be an input power of 15 watts, so there would be available for the peaks of power demanded by the loud speaker, up to two or three watts, without objectionable distortion.

In the accompanying table are given the possible outputs (without appreciable distortion) of the types of triodes used as output tubes:

Type	Plate, Voltage	Grid, Bias	Maximum Milliwatts, Output
120	135	22.5	110
112*A*	135 157	9.0 10.5	120 195
171*A*	90 135 180	16.5 27.0 40.0	130 330 700
210	210 300 350 400	18.0 22.5 27.0 31.5	340 600 925 1,325
250	250 300 350 400 450	45.0 54.0 63.0 70.0 84.0	900 1,500 2,350 3,250 4,650
245	180 250	33 50	750 1600

23. Necessity of Suitable Grid Bias.—The grid of an amplifying tube should never draw appreciable current; this is one of the prime requirements if amplification is to be accomplished without distortion of the signal.

The potential of the grid of an amplifier is evidently fixed by the voltage of the signal superimposed upon whatever grid bias there is used. Thus if the signal voltage is 1 volt (effective) the signal makes the grid fluctuate 1.41 volts up and down around whatever its normal potential may be. If the grid bias is -4.5 volts the grid potential will fluctuate then between $(-4.5 + 1.4)$ and $(-4.5 - 1.4)$ or between -5.9 and -3.1 volts. As a grid will not draw current unless the grid swings positive, this grid will draw no current.

Now suppose the signal increases up to 4 volts (effective). The grid potential will now fluctuate between $(-4.5 + 5.6)$ and $(-4.5 - 5.6)$ or between 1.1 volts positive and 10.1 volts negative. During the short interval of time that the grid was positive it would draw current from the circuit to which it is connected, and this will result in signal distortion. The more positive the grid swings the more distortion there is produced; in bad cases of this kind the listener is given the impression that the loud speaker is "rattling"; the rattle is not a mechanical rattle, but is the result of the loud speaker giving a response to the badly distorted signal current.

The amount of bias used on the grids of the triodes of a well-designed amplifier increases with the successive tubes. In the R.F. amplifier stages the signal is weak and little or no grid bias is required; generally a few volts are used.

The first A.F. triode may have a bias of 9 volts and the second A.F. triode (generally the output tube) may use as high as 100 volts.

Referring to the table on p. 242, it is seen that a 210-type tube, with 300 volts on the plate, should have a 22.5 grid bias; it can then stand a signal strength of $\frac{22.5}{\sqrt{2}}$ or about 16 volts before distortion due to grid current sets in. With this signal strength (16 volts effective) the possible power output is 600 milliwatts, about right for the "peak value" of a house signal.

The type 250 triode, using a 450-volt plate supply and a 84-volt grid bias, could stand an input signal of $84/\sqrt{2}$ or 60 volts

(effective) and would then deliver to the loud speaker an undistorted output of 4.65 watts.

24. The Push-pull Amplifier.—As has been mentioned before the amount of power which a triode can deliver to the loud speaker is only a small fraction of the power input to its plate circuit, the reason being that as the signal output power increases beyond a certain amount the triode (even though its grid is drawing no current) will distort the signal. This is primarily due to the fact that the relation between plate current and grid potential is a curved line, not a straight line.

By using two triodes in the output stage, instead of one, and connecting them together in a special manner, part of this distortion due to the non-linearity of the plate current-grid potential curve is eliminated, and each of the triodes can deliver to the load more undistorted power than if it were used alone.

The special connection is shown in Fig. 164; here the output of the "push-pull" stage is shown as supplying the input voltage for another triode; this scheme is sometimes used in a broadcast transmitter, but in radio receivers the transformer T_2 would be the output transformer of the set, the secondary connecting directly to the loud speaker. In the case of the oscillating armature cone speaker the output transformer would have a step-down ratio of about 2 to 1 and if a dynamic, or moving coil, speaker is used, the step-down ratio will be about 30 to 1. This ratio should be sufficient to make the resistance of the loud speaker appear to the output tube as equal to about twice its own plate circuit resistance.

By inspection of Fig. 164 it will be seen that when the signal, from triode A, makes the grid potential of triode B increase it makes the potential of the grid of triode C decrease. Thus the plate current of triode B increases while that of triode C is decreasing and vice versa. This action gave rise to the name *push-pull.* The decreasing and increasing plate currents give additive effects in transformer T_2 in so far as the signal is concerned, and the most disturbing factor of distortion, the second harmonic of the signal voltage, is practically eliminated.

For equal quality of signal the possible output of two triodes arranged in push-pull connection is about five times as much as the output of one tube used alone. It will be understood of course that the two triodes must be reasonably well matched, as to characteristics, if the advantage of the arrangement is to be obtained.

25. Antennas for Broadcast Receivers.—A few of the broadcast receivers, particularly those of the super-heterodyne type, use a loop for picking up their signals; perhaps ten turns of wire, wound on a frame about 18 inches square, picks up sufficient signal for the amplifiers to operate efficiently.

All amplifiers are noisy, of themselves, to some extent; the electron emission from the filament is not exactly uniform, sometimes the electrical action in dry cells gives rise to noises, and if the power for the A, B, and C circuits is obtained from a rectified alternating-current supply there is always some residual hum, and also

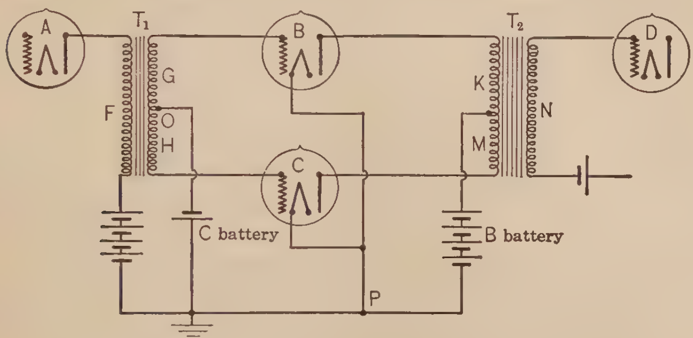

FIG. 164.—Showing a "push-pull" stage of amplification.

other noises set up by motors starting and stopping, lights being turned on and off, etc.

These noises set up by electrical disturbances *in the set* constitute a background of noise which is amplified along with the signal; the signal must always be much louder than this background of noise and it is the function of the antenna to pick up sufficient signal to satisfy this condition. If there were no background of noise an antenna a foot or two long or even none at all would be sufficient to pick up signals; or even the coils of the receiver itself would act like small loop antennas and pick up a signal, which with great amplification would operate the loud speaker.

In order to keep the ratio of noise to signal as small as possible it is advisable to pick up as much signal as is convenient; the greater the signal picked up the less amplification is required (which in general means less distortion) and the less evident is the background of noise.

Too long an antenna, however, makes it impossible to tune in

broadcast frequencies, so a compromise has to be reached. A single-wire outdoor antenna about 50 feet high and 100–150 feet long makes the most suitable antenna in general; it should be reasonably well insulated, by small porcelain knobs, and should run through a porcelain tube or other insulator where it enters the house. The ground connection for the antenna circuit should be made to the water pipe system of the house. If such is not available a piece of pipe driven into the ground as far as possible (so that its lower end is in permanently moist earth) will serve.

For an indoor antenna a few wires connected in parallel and fastened by insulators to the rafters of the house serve well as the top part of the antenna. The down lead can be a single wire running down inside the wall (for a wooden house) to the room where the radio receiver is located.

In an apartment house, where an outside antenna is generally not feasible, a wire run around the room on the top of the picture molding generally works reasonably well; if the house is of steel construction it is sometimes impossible to get a signal of usable strength because of the absorption of the signals by the framework of the building. In such a case the best signal will generally be obtained by running a wire up the wall, as close to one of the steel columns of the building as possible. The radiator makes a reasonably good ground for apartment house installations.

26. Sources of Power for A and B Circuits.—Within the past year the battery-operated set has practically disappeared from the market. One of the reasons was the very considerable cost of power. The high-powered output tubes, using say 60 milliamperes at 400 volts, require 300 cells of B battery and the current drain gives them a very short life; the consequent cost of battery maintainance became prohibitive. And, of course, the storage battery, with its requisite charging apparatus is a nuisance.

The development of the alternating-current filament triode, using about one ampere at two or three volts, solved the storage battery problem except for the detector; here the heater type of tube permits the use of alternating current, not to heat the cathode directly but indirectly. This is necessary because the use of an alternating-current filament tube for detector produces an unavoidable hum.

For the plate circuit supply rectified alternating-current power is used. A transformer takes power from the 110-volt power line

and raises it to about 800 volts. This secondary winding is tapped at its mid-point to form the return path for the rectified current flowing, in turn, in each half of the secondary winding. Figure 165 shows the general arrangement, the transformer T, of about 50 watts rating steps up the 110-volt supply to about 800, the center tap of the transformer passes directly to the B supply circuit. Each outside terminal of the secondary goes to a rectifier, A and B, which are generally of the hot filament type, that is, diodes. The two rectifier-output terminals are connected together to form another line of the B power supply.

The condensers C_1 and C_2 and the choke coil L tend to smooth out the fluctuations of the rectified alternating-current supply. If

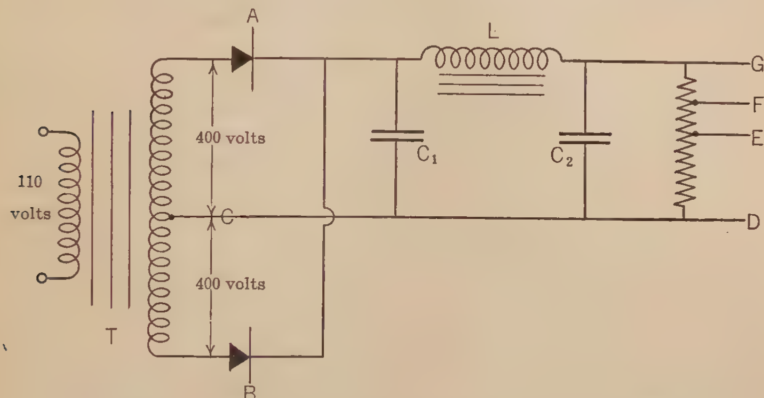

Fig. 165.—A simple full-wave rectifying circuit and filter.

one coil and two sets of condensers are not sufficient to eliminate the ripple to the desired degree, another coil and another condenser are added, making a two-section filter instead of the one-section one shown in Fig. 165. Across the supply terminals G–D is connected a reasonably high resistance, say 10,000 ohms. Taps on this resistance at suitable points give the proper voltage for detector and amplifiers. The power tube used for the output circuit generally uses practically all of the voltage G–D.

In Fig. 166 is shown more in detail the arrangement of the supply circuit. The two terminals G–D correspond to the same lines of Fig. 165. The point E in the resistance G–D forms the filament connection and is grounded; it connects to the adjustable mid-point of potentiometer P, across the secondary S of the filament

supply transformer. Connection A goes to the plate of the output tube, it is about 400 volts higher in potential than point E. Point B, at about 100-volt potential, goes to the plates of the amplifying tubes; point C goes to the plate of the detector tube. Point F forms the grid connection for the amplifying tubes; it gives a negative bias of about 9 volts. Point H forms the grid connection of the power tube; it gives a negative bias of about 40 volts. Condensers, generally of about $2\mu f$ each, are shunted across the various supply terminals, for the double purpose of further eliminating the ripples of the rectified power supply and of preventing fluctuations

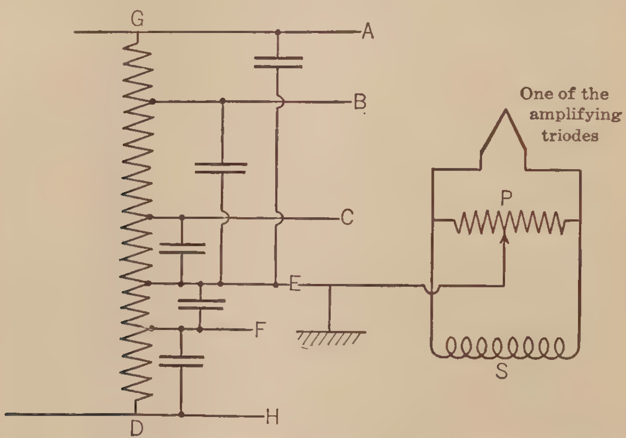

Fig. 166.—The filtered output of the circuit of Fig. 165 is generally supplied to a "potential-divider" or tapped resistance, to supply the various plate voltages required for a set, as well as the required C bias voltages.

in the plate current of some tubes of the amplifier materially affecting the plate voltage of others. Such interaction, if not prevented, results in a peculiar voltage pulsation in the plate supply, frequently called "motor boating."

27. Filters.—This is the name applied to a group of resistances, coils, and condensers (or possibly only two of these) arranged in such a fashion that currents of certain frequencies flow readily through the circuit while others encounter such a high impedance that they are essentially eliminated from the circuit.

There are three general types: *high-pass*, *low-pass*, and *band-pass* filters. The high-pass filter passes readily all frequencies above a certain value and practically blocks the frequencies below this

certain value. The low-pass filter permits low frequencies to pass and practically blocks the higher frequencies. The band-pass filter permits the ready passage of currents of frequencies within certain limits, and greatly impedes currents of frequencies either higher or lower than this band.

The general idea of a filter is shown in Fig. 167; with a constant magnitude of voltage impressed upon its input terminals the volt-

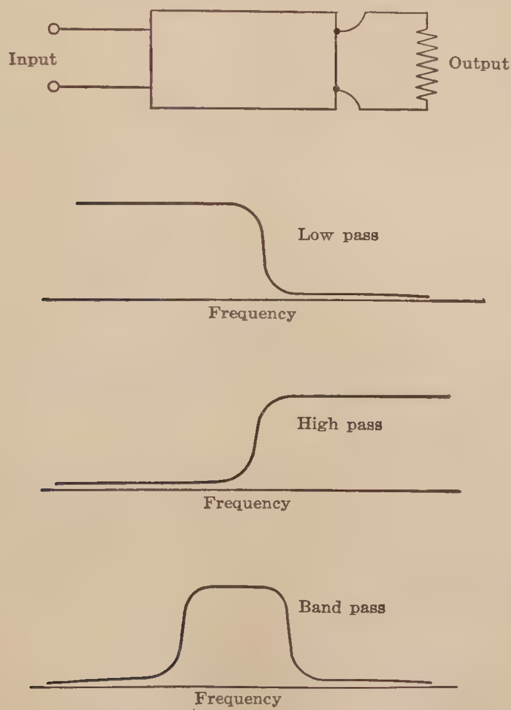

FIG. 167.—Characteristic curves of various types of filters.

age across the output terminals, as the input frequency is varied, has the form of the various curves there given. The sharpness of the "cut off," that is, how suddenly the filter changes its impedance as the frequency is varied, depends in general upon the size, and therefore on the cost, of the filter. The lower the resistance of the coils used, and the more sections there are to a filter, the sharper is its change from high to low impedance.

In Fig. 168 are shown the general forms of filters used for low

pass, high pass and band pass. Three sections each of the low- and high-pass type are given, and one section of the band pass.

A simple calculation, say, of the low-pass type, will show the reason for the peculiar performance of filters. We will suppose that each coil in the low-pass filter of Fig. 168 has 10 henrys inductance and a resistance for continuous current of 10 ohms, and, for

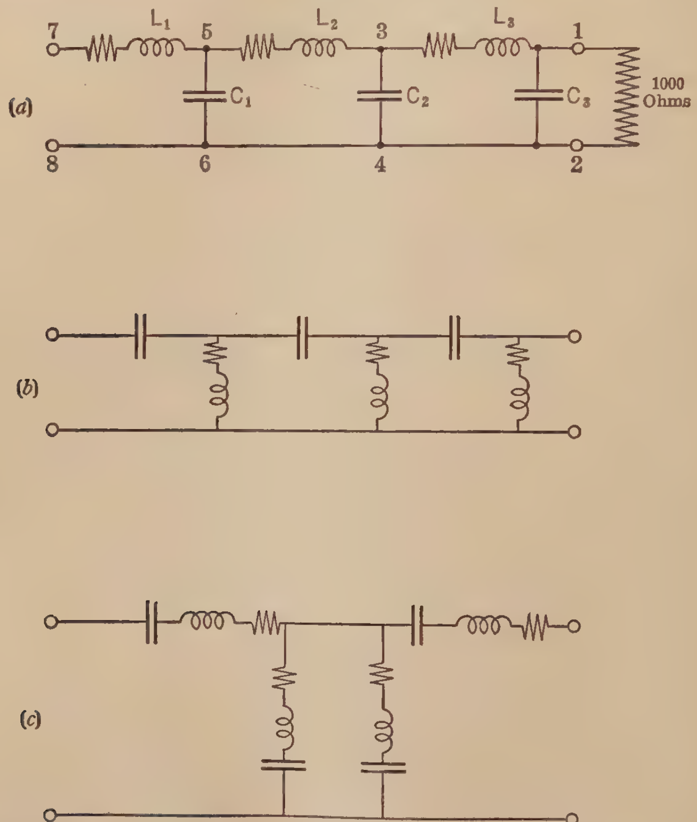

FIG. 168.—Circuit arrangements to obtain the forms of curves given in Fig. 167.

120 cycles, of 200 ohms, and that the condensers are each 5 microfarads. At 120 cycles the impedance of each coil is then 7540 ohms and the reactance of each condenser is 266 ohms.

Now suppose a pulsating voltage of $e = 100 + 50 \sin 2\pi 120t$ is impressed on the input terminals, what will be the current flowing in the 1000-ohm load? Will the ripple in the current of the load

be as pronounced as the ripple in the voltage impressed? Exact formulas are available for solving such circuits, but it can be solved approximately by very simple methods.

In so far as the continuous current in the load is concerned the filter offers only 30 ohms resistance, each coil having a continuous-current resistance of 10 ohms. We next notice that the impedance of the remainder of the filters connected across each condenser does not materially affect the impedance from one terminal of the condenser to the other. Thus the reactance of C_2 is 266 ohms, and across this is the coil L_3 in series with the condenser C_3 shunted by the 1000-ohm load. The impedance of the L_3–C_3-load combination is about 7300 ohms; and evidently shunting the condenser C_2, having a reactance of 266 ohms, by an impedance of 7300 ohms, will not greatly affect the impedance across circuit points 3–4. Actually, shunting the L_3–C_3 combination across points 3–4 (between which points condenser C_2 is connected) will increase the impedance between points 3–4 from 266 ohms to about 273 ohms, a negligible change when the analysis is only approximate, as we are attempting here.

In the same way then the reactance across the circuit at points 5–6 will not be appreciably affected by the L_2–C_2–L_3–C_3 combination connected in parallel with C_1. Having established this possible simplification of the network we can easily answer the question about the form of current through the load.

The circuit L_1–C_1 offers an impedance of approximately 7300 ohms; the current due to the ripple voltage, $50 \sin 2\pi 120t$, can then be calculated and so the drop across C_1 can be calculated. It will prove to be $\dfrac{266}{7300} \times 50 = 1.82$ volts.

This voltage is impressed across the circuit L_2–C_2 and so produces a certain current here; of the impressed voltage, 1.82 volts, a certain fraction will appear across C_2. The amount of this voltage across C_2 is $\dfrac{266}{7300} \times 1.82 = 0.066$ volt. And this voltage impressed across the L_3–C_3 circuit will set up across the condenser C_3 a voltage of 0.0024 volt. And finally this voltage will produce in the load a current of $\dfrac{0.0024}{1000} = 0.0000024$ ampere. The continuous current through the load is $100/1030 = 0.097$ ampere.

So the voltage across the load is $0.097 \times 1000 = 97$ volts of steady voltage and 0.0024 volt of pulsations. *The pulsating component is therefore* 0.0025 *per cent of the steady voltage and at the input terminals of the filter it is* 50 *per cent of the steady voltage.*

This approximate analysis serves well to show how filters can be used to " smooth out " the ripples from the voltage of a rectified alternating-current supply. Similar analyses could be carried out for the (*b*) filter (high pass) of Fig. 168; the band pass filter ((*c*) of Fig. 168) does not lend itself to a simple analysis.

28. A Typical Broadcast Receiver.—In Fig. 169 is shown the complete circuit diagram of a well-designed modern broadcast receiver, of the simpler type; the present tendency is to use a push-pull stage for the output and more recently the push-pull principal has been used for the last two audio-frequency stages. This, of course, costs more to build, and more to maintain, than if single tubes are used in each stage, but the quality is improved.

Referring to Fig. 169 we will analyze the circuit from the antenna end. Connection posts are provided for either a long or short antenna. The inductance in this circuit is designed for a short antenna and there is provided a small condenser in series with the " long antenna " connection, to make it act like a short antenna.

All of the four tuned radio-frequency circuits use similar coils and condensers, and all condensers are controlled from one dial. The effect of the antenna, coupled to the first tuned circuit, is to mistune it, compared to the others, so this first tuned circuit has some of its inductance placed in a small adjustable coil, labeled in Fig. 169, " Antenna." All of the apparatus is mounted on an aluminum bed plate and the various " ground " markings on the connection diagram indicate connections to this aluminum plate.

In series with the grid of each radio-frequency triode there is a small condenser, marked C_2, for the first triode. This condenser is adjusted at the factory; it serves to control the regeneration in the radio frequency circuits. This serves to make the set stable (non-oscillatory) instead of employing one of the neutralizing schemes given on p. 222 et seq. The rotor plates of all four condensers are connected together for common mechanical control and the rotor plates of the condensers connect to ground.

The voltage gain of the three radio-frequency amplifier stages

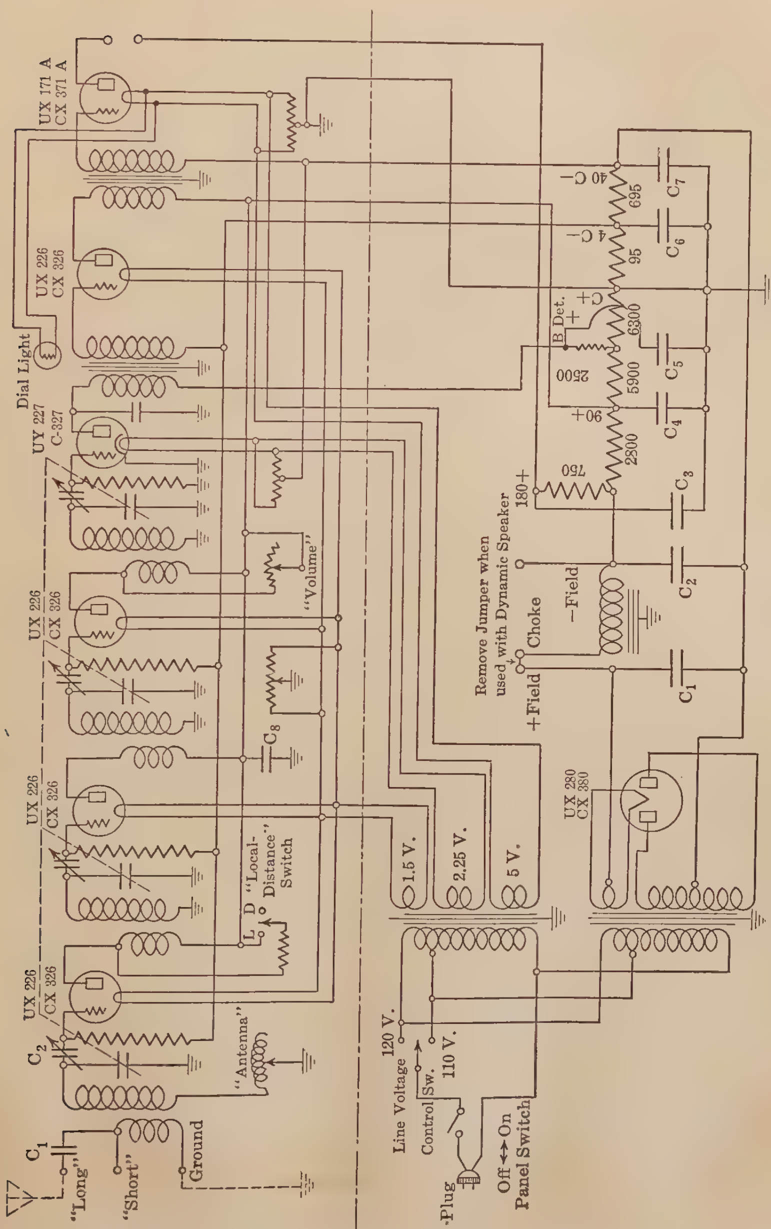

FIG. 169.—Circuit diagram of a typical broadcast receiver, with its power supply circuits.

varies somewhat with the frequency, being generally of the order of 1000-fold. Unless special precautions are taken to prevent it, the amplification is much greater at the high frequencies than at the lower. A representative curve of the performance of a commercial three-stage radio frequency set is shown in Fig. 170; the voltage gain is about 200 for the lower broadcast frequencies and is 3000 for the highest broadcast frequency.

With such a high voltage gain (say the average is 1000) the

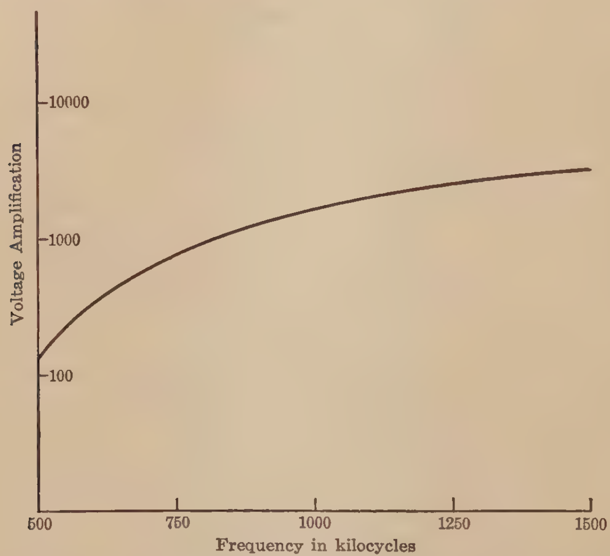

FIG. 170.—Typical voltage amplification-frequency curve of the radio-frequency stages of a modern broadcast receiver. The amplification is greater, and selectivity less, at the upper part of the broadcast frequency band than at the lower.

detector tube of Fig. 169 would be greatly overloaded by the signal of a nearby station unless precautions were taken to prevent it. In the receiver shown in Fig. 169 there is a "local-distance" switch. When thrown to the "local" position the plate coil of the first radio-frequency triode is shunted by a low resistance, thus greatly reducing the voltage gain of this stage.

The power supply for the plate circuits of the radio-frequency tubes is shunted to ground by condenser C_8. The alternating-current supply for the filaments of the R.F. triodes is shunted by a

potentiometer (close by condenser C_8) the sliding contact of which is grounded. This sliding contact is properly adjusted at the factory, to minimize the " hum " in the set.

The normal volume control of the set is obtained by a variable-resistance shunt across the plate coil of the last R.F. amplifier. It is marked " Volume " in Fig. 169. The maximum value of the resistance is about 2000 ohms.

The detector tube of the " heater " type, its filament requiring $2\frac{1}{4}$-volt 60-cycle supply. Across this supply is a potentiometer, the sliding contact of which goes to a negative " C " circuit of about 40 volts. The plate coil of the detector tube (primary coil of the first audio-frequency transformer) is shunted by a condenser, to furnish a low impedance path for the radio-frequency components of the plate current.

The first audio-frequency triode has a negative supply for its grid of 4 volts and a plate supply of 90 volts. The second A.F. tube is of special design and is called the *output* tube. It has a lower amplifying factor than the others and is of much lower plate circuit resistance. The negative grid bias is 40 volts, its plate voltage is 180, and its filament requires a 5-volt supply.

In the lower part of the diagram is shown the power-supply unit. Two transformers are shown, one for plate supply and one for filament supply; there is no need for two transformers, except as the heat generated is better dissipated from the two units than from one. It is better practice to use only one transformer, ventilated properly. Each transformer has an extra primary tap, so that 110-volt or 120-volt supply may be used.

The lower transformer furnishes the plate supply for the set. It has two secondary windings, one for the filament of the rectifying tube and the other for the plate voltage. This second winding generates about 700 volts and has a center tap. There are then 350 volts available in each half of the rectified cycle. Condensers C_1 and C_2 are built to stand 600 volts and are of a few microfarads each. The iron core choke coil between them has about 50 henrys inductance.

The rest of the circuit is a capacity-resistance filter; each of the condensers is about $2\mu f$ and the resistances have the values shown in the figure. The resistance in series with the detector plate supply tends to prevent distortion. The possible power output of this receiver is about 0.5 watt, which is plenty for the average

house installation, using the cone speaker. If a dynamic speaker is to be used a possible power of about 5 watts is required to take advantage of the greater capacity of this type of speaker; a push-pull circuit using type UX 250 or 245 tubes is then required. In the set shown in Fig. 169 certain posts and connections are indicated for use with such a push-pull amplifier.

PROBLEMS

CHAPTER I

1. If there are 10^{24} free electrons per cubic centimeter of copper, how fast are the electrons progressing down a wire having a cross-section of 1 square millimeter, if the wire is carrying 10 amperes? (Charge on one electron—1.59×10^{-19} coulomb.)

2. Assume that the mass of a copper atom is 100,000 times that of an electron, and that an electron, moving with a speed of 100 feet per second, strikes a stationary copper atom, and that after rebound the electron has half of its original energy, and the atom has the rest. What are the speeds of the atom and electron after collision?

3. A 110-volt, 60-cycle power line has what maximum potential difference? How many times per second does this occur? A 25-cycle current having a maximum value of 500 amperes has what effective value? If the current in a radio antenna is 25 microamperes, with a frequency of 1,000,000 cycles per second, what is the maximum value of the current?

4. A 22.5-volt, 5-lb. B battery is discharged intermittently at a rate of 50 milliamperes. Its average voltage during the discharge period is 20 volts, and it costs $0.95. What is the cost of energy from this battery (per kilowatt-hour) and how does this compare with commercial rates?

5. The filament of a type 199 tube is 2 in. long, and has resistance (hot) of 50 ohms. If it is made of tungsten (specific resistance, when red hot, 16 times that of copper at room temperature) what is its cross-sectional area, in circular mils, and what is its diameter?

6. The resistance of nickel is 6.2 times that of copper. What is the resistance of a nickel ribbon 8-in. long, 0.001 in. thick, and 0.08 in. wide?

7. In the primary winding of an amplifying transformer, there are used 6500 turns of No. 36 wire, average length per turn 6 in. and in the secondary 22,000 turns of No. 40 wire, average length per turn 8 in. What is the resistance of each coil?

8. The filament resistance (hot) of the output tube of a radio set is 4.2 ohms. If 5 volts are impressed what current does the filament take? If it is desired to cut the current down to 1.00 ampere how much added resistance is necessary? If German silver wire 0.02 in. diameter is used how many feet of it are required, its specific resistance being 30 times as great as that of copper?

9. A 5-lb., $22\frac{1}{2}$-volt B battery, discharging intermittently at the 50 milliampere rate compares how in weight per watt-hour of capacity with a 6-volt, 100-ampere-hour lead cell weighing 70 lb.?

10. A resistance of 16,000 ohms is connected across the 180-volt taps, of a "B eliminator" unit. How many watts are being used in it?

11. The voltage between the filament and plate of a vacuum tube is 350 and the current is 60 milliamperes. How much power is used in the tube?

12. Calculate the inductance of a cylindrical coil 4 in. in diameter, the winding being 2 in. long (axially) and there being 35 turns in the winding? Calculate the inductance in centimeters, microhenrys and millihenrys?

13. A coil 3 in. in diameter with a winding 2 in. long has an inductance of 200 microhenrys. With how many turns per inch is the coil wound?

14. If in the above coil the winding is pulled out (to space the successive turns) until it is 4 in. long, about how much will the inductance be?

15. What is the reactance of a 200 microhenry coil at a frequency of 1000 kilocycles? Of the same coil for a frequency of 600 kc.? At 1500 kc.?

16. The inductance of the primary coil of an audio frequency transformer is 55 henrys. What is its reactance for a frequency of 40 cycles per second? For a frequency of 3000 cycles per second?

17. If 5 volts of each of the above frequencies is impressed on the coil how much current will flow (resistance being neglected)?

18. In a by-pass condenser (as in Fig. 14) the waxed paper is 0.002 in. thick, the value of K is 2.2, and the width of the tin foil plate is 3 in., how long must be the tin-foil plates of a 1-μf condenser?

19. In a semicircular variable tuning condenser there are seven moving plates and eight fixed ones. The radius of the plates is 2 in. and the distance between the moving and stationary plates is $\frac{1}{32}$ in. What is its maximum capacity, in μf?

20. If a 1-μf condenser is connected to a 110-volt, 60-cycle line, how many milliamperes of current flow?

21. In a radio receiver the tuning condenser is set at the value of 0.000150μf, the voltage impressed is 0.60 volt, and the frequency is 1200 kc. How many milliamperes of current flow into it?

22. The condenser formed by the grid and plate of an amplifying tube has a capacity of 8$\mu\mu f$. If the voltage between grid and plate is 5 volts, at a frequency of 20,000 kc., how many microamperes of charging current flow?

23. The neutralizing condenser of a radio receiver is made of two pennies placed close together and parallel to each other. If the capacity must be 4$\mu\mu f$ how far apart must the pennies be?

24. A coil of 0.6 henry and 30 ohms resistance is connected to a 110-volt, 60-cycle line. How many amperes flow and what is the phase difference of voltage and current?

25. A coil having 50 ohms resistance, connected to a 110-volt, 25-cycle line draws 1.2 amperes. What is its reactance and inductance? What is the power factor of the coil?

26. A condenser of 20μf must be in series with how much resistance if it draws a current of 0.5 ampere from a 110-volt, 60-cycle line? What is the power factor of the circuit?

27. If a resistance of 5000 ohms is in series with a condenser of 0.0001μf and 5 volts at 400 kc. is impressed on the circuit, how much current flows?

PROBLEMS

CHAPTER II

1. An antenna radiates 650 watts when the current in it is 7 amperes. What is its radiation resistance?

2. A coil of 250μh in series with a condenser of 0.00012μf offers how much reactance to a current of 1150-kc. frequency?

3. A coil of 0.214 henry and 10 ohms resistance is in series with a condenser of 20μf is connected to a 110-volt 60-cycle line. How much current flows and what is the power factor? How much power is used? What is the voltage across the coil? Across the condenser?

4. A coil of 150μh inductance and 27 ohms resistance is in series with a condenser of 0.00026μf, having negligible losses. If one volt at 1500 kc. is impressed, how much current flows? Does the current lead or lag, and how much?

5. In problem 3 what value should the capacity have to bring about the condition of resonance, and what is the power factor at this frequency?

6. In the circuit of problem 5 if the maximum safe voltage on the condenser is 300 volts, what is the highest safe voltage to impress on the circuit?

7. A coil of 175μh inductance requires what capacity in series with it to establish resonance in a 1000-kc. circuit?

8. If a variable condenser, used with a 250-μh coil, is to tune for frequencies between 600 kc. and 1500 kc., what must be its maximum and minimum capacity?

9. A wave meter has a condenser with a minimum capacity of 0.000060μf. Its scale is marked from 500 kc. to 1500 kc. What is the inductance of its coil and what is the maximum capacity of the condenser?

10. A coil of 200μh has a resistance of 8 ohms. What condenser is required to give resonance at 750 kc.?

11. With one volt impressed on the circuit of problem 10 calculate the current for frequencies from 740 kc. to 760 kc., calculating the current for points separated from each other by 2 kc.

12. Calculate the decrement of the circuit of problem 10 by the use of formula 29 and check the value from the curve of prob. 11, using formula 28.

13. A resonant circuit uses a coil of 300μh inductance and 7.2 ohms resistance at the resonant frequency, 450 kc. If the resistance of the condenser may be neglected what is the decrement of the circuit? What is the power factor of the coil? What is the ratio of coil reactance to its resistance?

14. A coil of $L = 0.214$ henry and 6 ohms resistance is in parallel with a condenser of 15 microfarads, the condenser being in series with 13 ohms resistance. The combination is connected to a 110-volt, 60-cycle line. How much current flows in each branch of the circuit and how much flows in the line? What is the line power factor?

15. For problem 14, what is the line impedance and what are the resistance and reactance of the line?

16. In the circuit of problem 14, what must be the frequency of the line

to result in parallel resonance? What will be the line current? Line impedance? Line resistance?

17. A coil of $L = 250\mu h$ and 7 ohms must be shunted by what capacity to give parallel resonance for a 960-kc. supply voltage? What will be the resistance of the parallel circuit?

18. Assuming that the thickness of paper required for a filter condenser of a given capacity is directly proportional to the voltage used, how does the weight of paper required vary with the voltage for which the condenser is rated?

19. Assuming the minimum capacity of a condenser is $15\mu\mu f$ and that of the circuit to which it is attached is $10\mu\mu f$, what inductance must the coil have if the highest frequency for which the circuit is to be tuned is 1500 kc.?

20. If the condenser of problem 19 is to be a straight-line frequency condenser, with a scale marked 0 to 100, and the lowest frequency of the circuit is to be 600 kc., calculate the condenser capacity for settings of 20, 40, 60, 80, and 100.

21. The above condenser is connected to the input circuit of a triode, this having a resistance (grid to filament) of 200,000 ohms. Change this shunt resistance to an equivalent series resistance for condenser settings of 0, 20, 40, 60, 80, and 100.

22. If the losses in the condenser itself are negligible and the coil has a resistance of 12 ohms at 1500 kc. and 4 ohms at 600 kc., what is the decrement of the circuit for these two frequencies?

23. Referring to Fig. 35, assume that the coil L has an inductance of $20\mu h$, that the frequency of received signal is 1000 kc., that the condenser in the wave trap has a capacity of $0.0005\mu f$ and negligible losses, that the coil in the wave trap has a power factor of 2 per cent, that the L_1–C_1 circuit has a negligible effect on the impedance of L, and that the interfering frequency is 980 kc. What is the ratio of the current from the interfering signal through L to that through the wave trap?

24. The spark signal from a ship has a wave length of 750 meters. The inductance in the antenna circuit is $400\mu h$ and the antenna resistance is 12 ohms. How many waves are there in one wave train?

25. Referring to Fig. 35, if $L = 20\mu h$, $L_1 = 250\mu h$, $K = 10$ per cent, resistance of L_1–C_1 circuit = 8 ohms, resonant frequency of L_1–C_1 circuit = 1200 kc., what resistance does the L_1–C_1 circuit introduce in the antenna circuit, at its tuned frequency?

26. An antenna circuit has a total inductance of $62\mu h$ and the input circuit of the first amplifying triode, coupled to the antenna, has an inductance of $225\mu h$. The mutual inductance between the two circuits is $7\mu h$. What is the coefficient of coupling?

27. If the antenna circuit of the above problem has a total resistance of 32 ohms, and a capacity of $0.0003\mu f$, how much resistance does it introduce into the input circuit of the first triode, at the resonant frequency of the antenna?

PROBLEMS

CHAPTER III

1. If the power radiated from an antenna is 560 watts when the current is 6 amperes, what is the radiation resistance of the antenna? If the current is increased to 15 amperes, without changing the frequency, what is the radiated power? If with 6 amperes in the antenna the frequency is dropped to half its original value, how much power is radiated?

2. What is the frequency of the antenna current if the radiated wave is 1500 meters long? What is the frequency of a 450-meter wave? Of a 30-meter wave? Of a 10-meter wave?

3. If the decrement of a spark wave is 0.15, the wave length 600 meters, and the spark frequency 1000, what fraction of the time is the antenna radiating, on the assumption that the radiated energy is negligible after the current has decreased to 1 per cent of its initial value?

4. Broadcasting frequencies used today lie between 550 kc. and 1500 kc. What is the range of wave length used?

5. If the decrement of the overall resonance curve of a three-stage radio frequency amplifier is 0.4 per cent at 600 kc., and 0.5 per cent at 1500 kc., what is the frequency width included between the two " half energy " points of the resonance curve for these two frequencies?

6. An antenna 30 feet high has a total effective resistance at 1000 kc. of 16 ohms. If a 1000-kc. signal wave of 2 millivolts per meter passes by, what current is set up in the tuned antenna?

PROBLEMS

CHAPTER IV

1. Assuming 10^{18} molecules of gas per cubic centimeter at atmospheric pressure (760 mm. of mercury), how many are there when the pressure has been reduced to 1 mm.? When it has been reduced to 0.001 mm.? When it has been reduced to 10^{-6} mm.? How many at the highest vacuum attainable, namely 10^{-8} mm.?

2. On the average how far apart are the molecules of a gas at atmospheric pressure? At the highest attainable vacuum?

3. If a stationary molecule of copper is struck by an electron moving 50 miles per second, and if the copper molecule has 100,000 the mass of the electron (nearly the right proportion) and if the total kinetic energy is the same after collision as before, and if each has an equal amount of kinetic energy after collision, how fast are the molecule and electron moving after collision?

4. If the plate current of a diode is 1 milliampere with 25 volts on the plate how much will it be with 10 volts? With 50 volts? If with the plate voltage raised to 50 volts the plate current is 0.0012 ampere, what can you say about the filament emission?

5. If a triode has an amplifying factor of 8, and the plate current is 0.003 ampere with grid potential zero and plate potential 45, what is the plate current with grid voltage of -3 and plate voltage of 90? With negative grid potential of 9 and plate voltage of 170?

6. With plate voltage of 45 and grid voltage of 1 volt, positive, the plate current is 4 milliamperes and grid current is 6 microamperes, amplification factor of the tube being 7. What are plate and grid currents with plate voltage of 45 and grid voltage of plus 3 volts? With plate voltage of 45 and zero grid voltage?

7. With a plate voltage of 90 and zero grid voltage the plate current of a certain 201-A triode is 0.003 ampere and the amplification factor is 8. With an alternating voltage between grid and filament of one volt how much alternating current flows in the plate circuit?

8. Answer the above problem if there is a 10,000-ohm resistance in series with the plate.

9. The mutual conductance of a certain triode is 950 micromhos, the plate current (steady value) being 0.005 ampere. If a signal of 0.5 volt is impressed between grid and filament, between what values does the plate current fluctuate?

10. The interstage circuit of a certain R.F. amplifier using 201-A triodes ($\mu = 8$ and $R_p = 10{,}000$) consists of a primary coil of $L = 5\mu h$ and $R = 2$ ohms coupled 55 per cent to a secondary coil of $L = 250\mu h$ and $R = 7$. The secondary condenser tunes its circuit for the impressed frequency, 1000 kc. If the signal impressed on the grid of the first triode is 2 volts, what is the amount of fluctuation of the plate current, and how many watts are supplied to the tuned secondary circuit and what is the voltage across the condenser in this circuit?

11. A type 210 triode permits a signal of 20 volts when its plate voltage is 400 and grid bias is 32. Its amplification factor is 7.5 and plate circuit resistance (a.c.) is 3500 ohms. If the load circuit resistance in the plate is 5500 ohms, how much power can be delivered to the load?

12. A type 201-A triode has a plate circuit resistance of 12,000 ohms, and amplification factor of 8. If a signal voltage of 5 volts is used and the resistance introduced into the plate circuit by the coupled tuned circuit of the next triode is 1500 ohms (resistance of the plate coil itself being negligible), how much power is delivered to the tuned circuit?

13. A resistance coupled amplifier uses a triode with an amplifying factor of 5.2. With a plate voltage of 135 and grid bias of 9 the plate current is 0.004 ampere. The plate circuit resistance (a.c.) is 11,000 ohms. If a resistance of 20,000 ohms is used in the plate circuit how much B battery must be used to bring the plate current to 0.004 ampere? If one volt signal is impressed on the grid how much is the alternating voltage across the output resistance?

14. In the circuit of Fig. 81 the amplification factor of the first triode is 5, the inductance of L_1 is 50 henrys, the transformer turn ratio is 3.5, and the grid bias E_c is sufficient to prevent the flow of grid current in the second triode. The power factor of the coil L_1 is practically independent of frequency, being 0.3. For the first triode $R_p = 10{,}000$. With one volt on the input circuit what is the voltage on the second grid circuit for signal frequencies of 50, 100, and 200 cycles?

15. A circuit arranged as in Fig. 87 uses a triode which has an amplification constant of 8. The B battery is 135 volts and its current is 0.006 ampere. L_1 is $200\mu h$, R is 26 ohms, C is $0.0007\mu f$ and L_2 is $50\mu h$. What must be the coefficient of coupling between L_1 and L_2 to produce oscillations? If the circuit is set for this value of coupling and the circuit does not oscillate, what is probably the reason?

16. How must the resistance R, of coil L_1, vary with frequency if the same value of M is to be just sufficient to produce oscillations for various values of C, of Fig. 87?

17. If $L_1 = 200\mu h$, $R = 40$ ohms, $L_2 = 50\mu h$, $R_p = 5000$ ohms, $\mu = 5$ and the highest attainable coupling is 60 per cent, what is the lowest frequency the circuit can generate (Fig. 87)?

18. Referring to Fig. 88, $L_2 = 10\mu h$, $L_1 = 150\mu h$, $C = 0.0006\mu f$, $R_p = 5000$, μ of triode $= 6$, maximum value of K attainable $= 20$ per cent, what is the maximum resistance permissible in the oscillatory circuit if oscillations are desired?

19. What happens to the reading of a c.c. ammeter in the plate circuit of Fig. 88, when oscillations start? Suppose a grid condenser and grid leak are utilized in the circuit of Fig. 88, what would the answer be?

20. Referring to Fig. 90, coil $L_2 = 200\mu h$, $L_1 = 5\mu h$, and C_{gp} is $10\mu\mu f$. If parasitic oscillations occur what will be their wave length?

PROBLEMS

CHAPTER V

1. A skilled operator sends 30 words a minute, the average word having 5 letters. About what is the duration of one dot?

2. Referring to Fig. 97 the condenser C is made up of eight Leyden jars each of $0.002\mu f$ capacity. The spark gap is set to break down at 12,000 volts and there are 1000 sparks per second. How much power is drawn from the secondary circuit of the transformer? If this has an efficiency of 80 per cent and a step-up ratio of 110 to 20,000 volts, how much is the alternator current if the power factor of the primary circuit of the transformer is 0.75?

3. If the coil L_1 (of the circuit of Fig. 97) for the above problem is $16\mu h$, what is the frequency generated in this closed circuit?

4. If L_2 is $10\mu h$ and the antenna capacity is $0.0015\mu f$,what must be the value of the loading coil L_3?

5. If the M between coils L_1 and L_2 is $5\mu h$, what is the coefficient of coupling of the closed circuit and antenna circuit?

6. If 60 per cent of the high-frequency power generated in the closed circuit is transferred to the antenna, and this has an effective resistance of 15 ohms, what will the ammeter A read?

7. What is the decrement of the wave sent out from the antenna (quenched gap assumed) and how many waves are there per train?

8. If the antenna is to radiate a 600-meter wave what must be the combined inductance of L_2 and L_3 and what must be the inductance of L_1?

9. Referring to Fig. 102, the antenna has a capacity of $0.003\mu f$ and the

maximum capacity of condenser C is $0.001\mu f$. The set is to tune up to 3000 meters. Coil L_1 is wound on a 3-inch tube and coil L_2 on a $3\frac{1}{2}$-inch tube. Each coil is 3 inches long. With how many turns per inch must each coil be wound? From the wire table pick out suitable wires. Allow an increase in diameter of 0.004 in. for insulation.

10. If the continuous-wave signal of Fig. 108 is to set up in the phones of Fig. 102, a continuous current of 3 microamperes, what must be the magnitude of the high-frequency voltage across condenser C? (See Fig. 105 for this problem.) If the frequency is 100 kc. and the capacity of C is $0.001\mu f$, how much R.F. current is there in the L_2–C circuit?

11. If in the circuit of Fig. 113, L_1 is $50\mu h$, L_2 is $150\mu h$ and C is $0.0008\mu f$, what signal will be received with a note of 500 cycles?

12. To receive a 3000-meter wave, with a note of 1000 cycles, how much must C be if L_1 is $600\mu h$ and L_2 is $2600\mu h$?

13. Referring to Fig. 113, if L_1 is $100\mu h$, L_2 is $250\mu h$, C is the correct value for receiving a 600-meter wave, the tickler coil is $50\mu h$, resistance of the L_2–C–L_1 circuit is 14 ohms, resistance of plate circuit of the tube is 10,000 ohms, $\mu = 5$, what is the maximum permissible coupling between the L_1 coil and the tickler coil if a 500-kc. spark signal is to retain its characteristic musical quality?

PROBLEMS

CHAPTER VI

1. A microphone which, when idle has a resistance of 50 ohms is in series with a 50-ohm resistance and a 12-volt storage battery, of negligible resistance. If the voice makes the microphone increase and decrease its resistance 10 per cent, how much alternating current power is generated in the 50-ohm resistance? On the assumption that the power of the speaking voice is 10 microwatts, is this microphone and its circuit an amplifier as well as a converter?

2. Referring to Fig. 120, the condenser has a capacity of $100\mu\mu f$. The resistance of R is 500,000 ohms, voltage of E is 300, frequency of voice wave is 500, and the capacity of the transmitter changes plus and minus 10 per cent of its idle value. How much power, of voice frequency, is generated in R?

3. A 300-meter carrier wave is modulated by a 60-cycle wave having a third and fifth harmonic. What frequencies are sent off from the antenna?

4. The decrement of a circuit, sharply resonant for 1000 kc., is 0.008. What frequencies will be received with only one-half the power as is the carrier wave and what modulation frequency do these correspond to?

5. Referring to Fig. 129, the signal strengths A, B, and C, across the condenser C of Figs. 102 and 103 are respectively 0.3, 0.2, and 0.5 volt. With the triode detector the normal plate current is 0.0005 ampere, both with and without a grid condenser. Using the curves given in Fig. 105, draw the curve of phone current when crystal detector is used, and when triode is used, both with and without a grid condenser and leak. (Remember that with *no grid condenser* the triode rectifies with *increase* in plate current.)

6. In the circuit of Fig. 130 the plate choke coil has an inductance of 5 henrys. If with a modulation frequency of 100 cycles the plate voltage of

the oscillator increases and decreases from its average value by 150 volts, what is the amount of fluctuation in the current through the choke?

7. Referring to Fig. 133, if the weakest signal is 0.1 volt on the grid of the detector and the strongest is 0.5 volt, what are the corresponding diminutions in plate current of the detector (see Fig. 105)?

8. Why are the two desirable qualities of a radio receiving set, sharp selectivity and fidelity of reproduction, antagonistic?

PROBLEMS

CHAPTER VII

1. An antenna has an effective height of 40 feet and is acted on by a signal strength of 2 millivolts per meter. The resistance of the antenna itself is 25 ohms and the resistance introduced into the antenna circuit by the coupled tuned circuit of the first amplifying triode is 500 ohms. How much current flows in the antenna? How much power is wasted in the antenna and how much is supplied to the tuned input circuit of the triode?

2. If the resistance of the tuned input circuit of the above problem is 10 ohms and the reactance of the tuning condenser is 600 ohms, how much voltage is applied to the grid of the first amplifying tube?

3. If in problem 2 there are two stages of R.F. amplification and the signal applied to the grid of the detector is not to exceed 20 volts, what must be the maximum allowable voltage amplification per stage?

4. If the circuit of problem 1 is equipped with a crystal detector and phones instead of the amplifying triode, and the phones receive 2 per cent of the power supplied to the tuned circuit, and the phones have an effective resistance, at the signal frequency, of 5000 ohms, what is the current in the phones? If the efficiency of the phones in producing sound waves is 5 per cent (a possible figure with the phones close against the head) how much sound power is produced by the signal?

5. If by use of the circuit of Fig. 140 the effective resistance of the tuned input circuit of problem 1 is reduced from 10 ohms to 1 ohm and coupling of antenna and closed circuits is reduced to 31.6 per cent of its former value, how much power is supplied to the tuned input circuit by the antenna, and how much voltage is impressed on the grid of the triode?

6. The ratio of power output to power input of a certain triode circuit is 125. How many T.U.'s of gain per stage does the amplifier have?

7. At the end of a telephone line the power has decreased to 2 per cent of its original value. How many T.U.'s of amplification are required to bring the signal back to its original strength?

8. If the power of a signal is increased by 40 T.U.'s by a two-stage R.F. amplifier, how much is the voltage amplification per stage?

9. Referring to Fig. 148, the inductance in the tuned input circuit from A to B is $150\mu h$, the plate coil has $10\mu h$, and the inter-electrode capacity is $7\mu\mu f$. If the neutralization scheme is ineffective what will be the wave length of the probable parasitic oscillations?

10. In the scheme of Fig. 149 there are 25 turns from A to B and ten turns

from B to C. If the grid-plate capacity is $9\mu\mu f$ what must be the value of the neutralizing condenser C_2?

11. A super-heterodyne receiver having a 50-kc. intermediate frequency transformer, is receiving from a distant station a signal of 950 kc. A local station of different frequency tunes in at the same point of the dial. What is its frequency?

12. If a disturbing signal as above is to be tuned out by a wave trap and the condenser of the trap is to be on the same shaft as the signal tuning condenser, what type of condenser must be used in both circuits and why?

13. What is the disadvantage of having a radio receiver with high selectivity in its R. F. amplifier?

14. The arrangement of Fig. 165 is used for rectifying a 60-cycle supply, resulting in a pulsating output with a large 120-cycle and 180-cycle components. If the resistance G–D is 10,000 ohms, C_1 and C_2 are each $2\mu f$, and L is 50 henrys, what is the ratio of the 120-cycle, and of the 180-cycle, voltage ripple across $G-D$ compared to that across C_1?

15. Suppose a two-section filter of the type shown in Fig. 168 (a). The load resistance is 100 ohms, the coils have 0.6 henry each and 10 ohms resistance, and condensers are $10\mu f$ each. With 100 volts impressed, calculate the voltage across the load for 50, 60, 65, 70, 75, 80, 85, 90, and 100 cycles.

16. Suppose the units of the filter of problem 15 are rearranged as in diagram (b) of Fig. 168. Make the same calculations as for problem 15.

INDEX